The Externalities in Electricity Generation

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Abstract

Externalities exist where costs or benefits are unaccounted for in the market price of a commodity. The market price of electricity in a privatised Electricity Supply Industry such as the UK normally reflects the short term costs associated with producing electricity, rather than the longer term external effects of diversity, sustainability and the environment.

UK Government recognition of these externalities has resulted in legislation, economic measures such as taxes and schemes to encourage technologies with perceived lower external cost or added external benefit such as Renewable Energy.

This thesis examines the factors constituting externalities within the major electricity producing fuel cycles. Further it is shown that externalities may be specifically quantified at a local level in order to produce optimal welfare distribution. The wind energy fuel cycle is shown to be a prime example of an electricity production method entailing unmeasured externalities.

Specific analysis of electricity production from wind is used to develop a computer model, ExWind. ExWind enables the quantification of the associated project externalities which when evaluated together with all other cost and benefit factors provides the optimal project design.

Field studies making use of the ExWind methodology on existing and planned windfarm sites produce location specific monetary valuations for externalities. These results are in good agreement with previous qualitative studies of windfarm externalities. The genetic wind project optimisation in ExWind efficiently yields windfarm layouts significantly better than those designed by humans, while additionally producing optimal welfare distribution.

Declaration of Originality

I hereby declare that this thesis is my original work except where otherwise stated.

Gary Connor

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Abbreviations

AML	Arc Macro Language
BATNEEC	Best Available Techniques Not Entailing Excessive Cost
BETTA	British Energy Trading and Transmission Arrangements
BS	British Standard
CAP	Common Agricultural Policy
CCGT	Combined Cycle Gas Turbine
CCL	Climate Change Levy
CEGB	Central Electricity Generating Board
CHP	Combined Heat and Power
COM	Component Object Model
CV	Contingent Valuation
DNC	Declared Net Capacity
DNO	District Network Operator
DTI	Department of Trade and Industry (UK)
DTM	Digital Terrain Model
EA	Emission Allowance
EC	European Commission
ECU	European Common Unit
EIA	Environmental Impact Assessment
EMI	Electromagnetic Interference
ERC	Emmission Reduction Credit
ESI	Electricity Supply Industry
ESRI	Environmental Systems Research Institute
ESP	Electrostatic Precipitators
ETSU	Energy Technology Support Unit
EU	European Union
FBC	Fluidised Bed Combustion
FGD	Flue Gas Desulphurisation
GA	Genetic Algorithm
GHG	Green House Gas
GIS	Geographical Information System
GRP	Glass Reinforced Plastic
GUI	Graphical User Interface
IEA	International Energy Association
ILS	Instrument Landing System
IPC	Integrated Pollution Control
IPP	Independent Power Producer
IRR	Internal Rate of Return

kWh	Kilowatt Hour
LCA	Life Cycle Analysis
LCP	Least Cost Planning
LCDP	Least Cost Development Planning
LOS	Line of Sight
LPG	Liquefied Petroleum Gas
MB	Marginal Benefit
MC	Marginal Cost
MToe	Million Tonnes of Oil Equivalent
NA	Not Applicable
NETA	New Electricity Trading Arrangements
NDSI	Noise Depreciation Sensitivity Index
NINFFO	Northern Ireland Non Fossil Fuels Obligation
NFFO	Non Fossil Fuels Obligation
NFPA	Non Fossil Purchasing Agency
NGC	National Grid Company (UK)
NHS	National Health Service (UK)
NPV	Net Present Value
NSHEB	North of Scotland Hydro Electric Board
O and M	Operation and Maintenance
OCR	Optical Character Recognition
OFFER	Office for Electricity Regulation
OFGAS	Office for Gas Regulation
OFGEM	Office of Gas and Electricity Markets
OS	Ordinance Survey
PB	Payback
PC	Personal Computer
PDF	Probability Density Function
PES	Public Electricity Suppliers
PPP	Polluter pays Principle
PPP	Pool Purchase Price
PR	Public Relations
PUC	Public Utility Company (US)
PURPA	Public Utilities Regulatory Policies Act (US)
PV	Photo Voltaic
RAD	Rapid Application Development
RADCOM	Radio Communications Agency (UK)
RAM	Random Access Memory
RE	Renewable Energy
REC	Regional Electricity Company
RF	Radio Frequency
SCR	Selective Catalytic Reduction
SEPA	Scottish Environmental Protection Agency
SKr	Swedish Kronar
SNR	Signal to Noise Ratio
SRO	Scottish Renewables Order
SSEB	South of Scotland Electricity Board
TM	Transverse Mercator
UK	United Kingdom
US	United States

USD	US Dollars
VOR	VHF Omni-directional Ranging
VR	Virtual Reality
VRML	Virtual Reality Markup Language
WTA	Willingness To Accept
WTG	Wind Turbine Generator
WTP	Willingness To Pay
ZVI	Zone of Visual Intrusion

Symbols

a	Radius of WTG blade cross section (m)
A_1	Additional path loss transmitter to receiver (dB)
A_2	Additional path loss transmitter to obstacle (dB)
$A_g(x)$	Acoustic noise air attenuation (dB(A))
A_x	Additional path loss obstacle to receiver (dB)
A_t	Net cashflow for period 't' (£)
Al	Suns altitude angle (° above horizon)
A(P)	Annuitised average house price (£)
AVN	Annual value of noise (£)
Az	Sun's azimuth angle (° from due south)
b	Full radial extent of WTG wake (m)
C	Original signal (dB)
CO_2	Carbon Dioxide
D	WTG diameter (m)
D_S	Suns declination (latitude at which sun directly overhead)
E	Energy (J)
ET	Equation of time (s)
f(r)	Radial wind velocity profile function
g	Gravitational constant (ms^{-2})
$G_g(x)$	Acoustic noise ground attenuation function
I	Interference (dB)
L	Length of blade (m)
L_{Aeq}	Noise level equivalent to the mean sound energy level (db(A))
L_p	Observed acoustic noise (db(A))
L_{tod}	Acoustic noise level - time of day (db(A))
L_w	WTG acoustic noise (db(A))
$L_{year,obs}$	Acoustic noise level observed in a year (db(A))
Lat	Latitude (°)
Lon	Longitude (°)
LST	Local solar time
LSTM	Local standard time meridian
m	Initial WTG wake velocity ratio
n, N	A number
N_{day}	Day in the year
NDSI	Noise depreciation sensitivity index
NO_x	Nitrous Oxide
P	Power (W)
P_r	Pressure (Pa)

P_{ro}	Original Pressure (Pa)
$Pr(v)$	Weibull windspeed probability
$P(v)$	WTG power curve
r	Radial distance from WTG (m)
r_d	Discount rate (%)
R	WTG rotor radius (m)
R_g	Specific gas constant ($J.Kg^{-1}K$)
rlen	Roughness length
$rlen_a$	Roughness length reference 'a'
$rlen_b$	Roughness length reference 'b'
SO_2	Sulphur Dioxide
t	Time
T	Temperature (°K)
t_{sn}	Time of solar noon
v	Velocity (ms^{-1})
W	Weibull weighting factor
x	Distance (m)
x_d	Downstream distance to obstacle (m)
z	Height above ground (m)
z_{meas}	Height of windspeed measurement (m)
z_{obs}	Height of obstacle (m)
α	Weibull distribution shape parameter
β	Weibull distribution scale parameter
ΔG	Antenna discrimination factor
ΔU_m	Wind velocity deficit at wake centreline (ms^{-1})
Δv	Velocity change (ms^{-1})
γ	Environmental Lapse Rate ($°K.m^{-1}$)
λ	Signal wavelength (m)
ρ	Density ($kg.m^{-3}$)
ϱ	Porosity
σ	Radar cross section (sBm^2)
τ	Surface stress

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Chapter 1

Introduction

1.1 Thesis Background

The increasing worldwide demand for energy has seen an associated increase in demand for electrical energy. Figure 1.1 depicts world electrical energy demand [1]. The use of electrical energy brings great social and economic benefit yet substantial environmental and social cost. Studies have shown the benefits derived from electricity to be up to an order of magnitude greater than the associated costs [2], but, these costs must not be ignored. Traditionally, the price paid for electricity has been set according to the associated fuel, generation, transmission, distribution and auxiliary service costs.

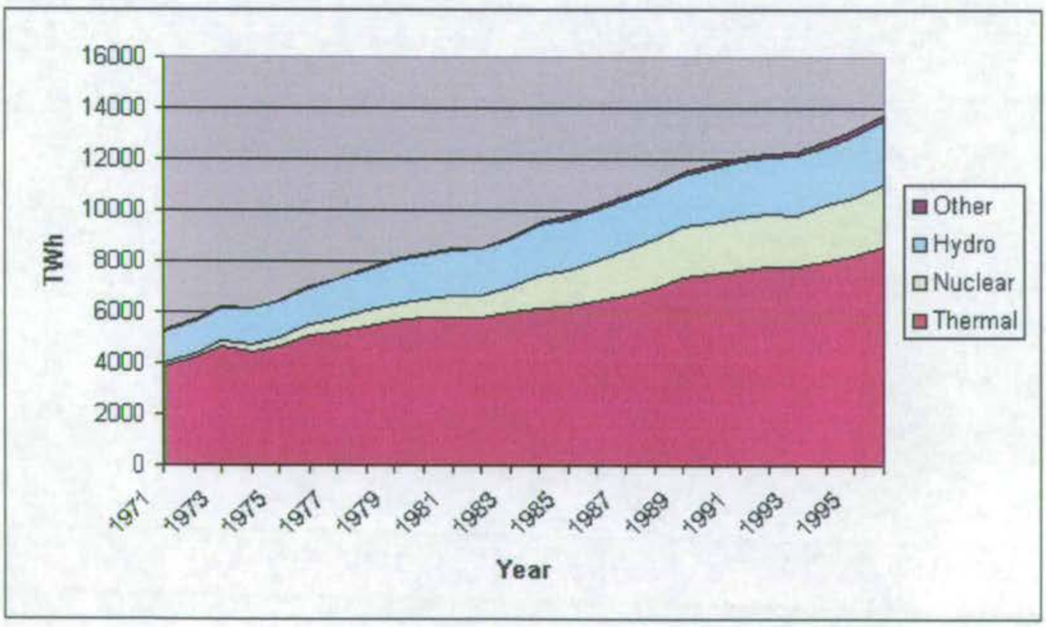

Figure 1.1: World-wide electrical energy demand.

Strategic comparisons between fuel cycles when planning new generating capacity were normally based on traditional least cost planning unless political compunction existed to purchase a specific fuel, for example, the pressure applied by successive British Governments to the Nationalised Electricity Supply Industry (ESI) to build power stations which used coal mined in the UK. Allowances were included in energy policy for security of supply and limitation of import dependency by a reliable, diverse range of generation options. The nuclear industry was heralded as providing these benefits, supplementing the large coal generation capacity. It is notable that the associated social and environmental matters were incorporated from a decidedly qualitative basis, that is, based on expert opinion of optimal welfare distribution, possibly in the favour of a special interest group, for example, the British coal industry.

Little systematic methodology that fairly quantified and incorporated all relevant factors existed to provide unbiased quantitative support in decision making. This encouraged both deliberate and involuntary biases when determining policy. Thus a sub-optimal market allocation resulted through the overexploitation of resources (typically environmental), their cost and benefit remaining unreflected in electricity pricing.

Since the early 1980's there has been an international realisation that the environmental and social costs attributed to energy use, including the production of electricity, may be significant. Examples of unaccounted for costs include, the probability of global warming due to increased atmospheric carbon dioxide (CO_2) levels [3], sulphur dioxide (SO_2) and nitrous oxide (NO_x) induced acid rain pollution across Europe and the radiation effects associated with the Chernobyl incident.

During the same period there has been a worldwide movement towards privatised electricity markets, optimum resource allocation being implemented through the mechanism of the liberalised market.

These two strands (environmental or social costs and liberalised markets) are often envisaged as being diametrically opposed and little effort has been made attempting to justify one against the other. However, it is recognised that the previously unaccounted for environmental and social costs require urgent international attention, and attempts are now underway to include them with the traditional costing elements when determining the electricity generation mix for the future. Such non-traditional costs, or sometimes benefits, are termed 'externalities'.

1.2 Externalities

Externalities may be defined as:

> the costs and benefits which arise when the social or economic activities of one group of people have an impact on another, and when the first group fail to fully account for their impacts [4].

An externality results from the lack of a suitable feedback mechanism for preferences. A specific externality exists, for example, when the National Health Service spends money to treat lung disorders associated with the pollution produced by coal fired power stations. This cost is not reflected in the market price of electricity produced from coal-fired stations and is therefore termed an externality or external cost. An externality would not exist if the cost to the NHS (or society) through pollution were optimally matched by the benefits from electricity produced in such a manner, assuming that there exists no better method for producing the same benefit at less cost.

The 'optimal' level of pollution considered acceptable changes with the perspective of the individual. That is, the polluter incurring private cost may see it in his interest to meet only the minimum regulatory level, while the public individual incurring the marginal social cost requires the optimal public social cost or utility. Figure 1.2 illustrates the external cost deriving from the gap between public and private costs.

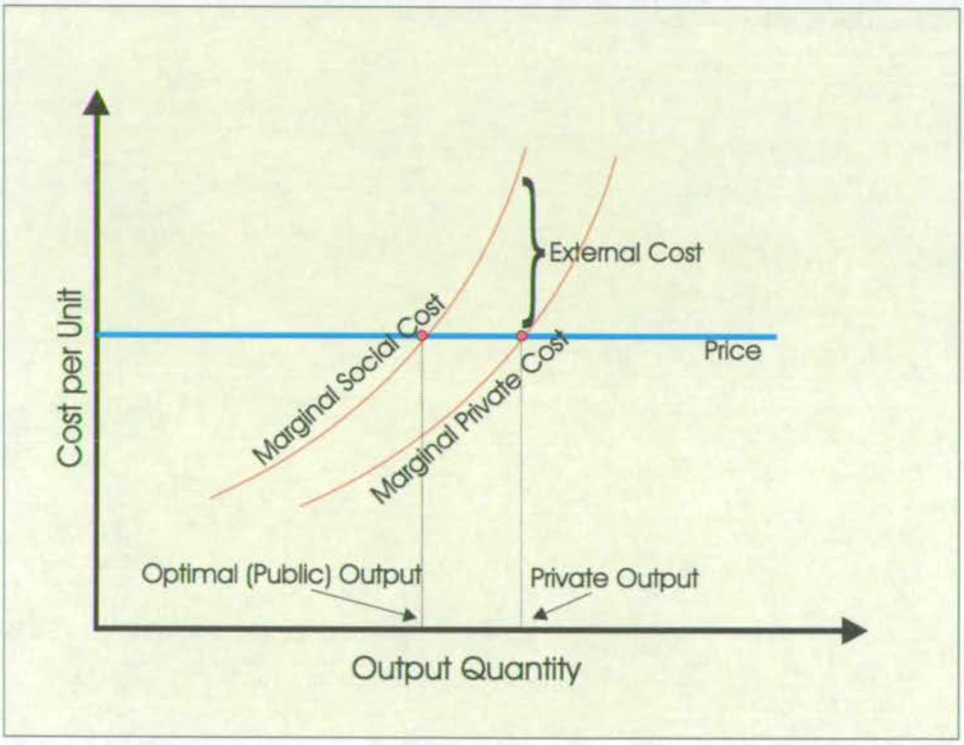

Figure 1.2: Private and public benefit.

Maximising the public benefit against the associated cost introduces the idea of welfare economics where social efficiency requires that the marginal social benefits and costs be equal. To produce such equilibrium infers that there is some measure by which to balance these two social outcomes, usually expressed in monetary terms. It is generally agreed that, within the broadly accepted principle of maximising welfare, it is the marginal social cost which is of relevance when determining the real market price of a good.

1.3 Aims and Objectives

The previous section presented a brief discussion on externalities and welfare economics. The study is expanded in the subsequent chapters to provide a full description of externalities, their implications to the UK Electricity Supply Industry (ESI), methods and measures attempting to account for them, specific identification of the external effects associated with each electricity generation cycle and the development of an impact pathway methodology implemented with regard to onshore windfarms. Results produced in a number of study analyses are evaluated and conclusions drawn.

The objectives of this study may be summarised as follows:

1. To identify and describe the externalities associated with electricity generation with regard to the UK ESI.
2. To examine and evaluate the past, present and future methods for the quantification of externalities and measures by which they may be included in Least Cost Planning (LCP).
3. To develop a methodology for the quantification of specific externalities in monetary terms.
4. To implement the methodology as a computer programme for an electricity generation technology particularly prone to externalities, that is, wind power.
5. To evaluate the possibility of producing maximal benefit from a windfarm by the optimal distribution or tradeoffs between traditional costs, traditional benefits and externalities.
6. To test the methodology for real windfarms with the computer model and subsequently evaluate the findings for future windfarm design and siting.

1.4 Chapter Summary

This thesis is organised into eight chapters. A summary of each chapter is presented below.

Chapter two introduces the economic theory of externalities before focusing on their specific appearance within various ESI structures. A discussion of the rationalisation for their inclusion leads into the currently applied methods for their inclusion. It is acknowledged that the quantification of externalities is possible but non-trivial. The chapter ends with a summary of the results from previous external cost studies and a general summary.

Following the definition and general scene setting concerning externalities, Chapter three concentrates on the UK ESI and its associated externalities. The Governmental role with regard to energy and environmental policy, legislation, regulation and as a part of the wider European Community (EC) is examined. Similarly the changes in the UK ESI structure are evaluated as to their capability of accounting for all costs including externalities. Current measures to include true-costing principles are discussed and those likely in the future alluded to. True Least Cost Planning (LCP) with regard to generation choice should include externalities, therefore all major UK fuel cycles are examined with respect to their externalities. Forecasts of the future UK generation mix according to current 'traditional' costing and according to the inclusion of externalities are compared. It is expected that a significantly different generation mix results if true-costing methods are introduced.

Chapter four concentrates on a particular generation option, that is, wind energy. Wind energy represents a new technology perceived to have environmental benefits (external benefit) and environmental impacts (external cost), it is therefore the chosen technology around which an externality quantification and welfare optimisation model is based. The history, specifics of energy output and traditional costing are summarised. In addition the implications of currently unquantified externalities at national and local levels are identified and discussed in detail. Methodologies for the monetary quantification of external cost are submitted and possible mitigation strategies outlined prior to the chapter conclusion.

The development of a software tool 'ExWind' to quantify, analyse and optimise the cost-benefit associated with an onshore windfarm is described in Chapter five. Basic software objectives, requirements and structure are initially outlined along with the decision to use geographic location as the basis on which to frame the previously derived impact pathway methodology. Data requirements are examined and appraised as regards their suitability. Finally, methods to reduce process time and increase software productivity, namely an initial windfarm site suitability filter and the use of genetic algorithms (GA) for wind turbine generator (WTG) layout optimisation, are introduced.

Chapter six builds on the background to ExWind outlined in Chapter 5. The specific methodology, algorithms and software structure are described. Each of the software modules evaluating and quantifying externalities are described in detail, frequent illustrations providing clarification. Further sections describe the costing of the traditional windfarm elements and the subsequent optimisation of the windfarm according to all costs and benefits by use of the GA layout solver. The final section describes the financial analysis module from which the user determines his acceptance or rejection of the ExWind suggested project. A summary alludes to the major findings of the chapter.

Chapter seven examines a number of case studies for which ExWind is utilised. The case studies determine the accuracy of ExWind in:

- the comparison to the design of existing windfarms,
- the quantification of the externalities associated with an existing windfarm

- and the automatic selection, evaluation and optimisation of a proposed windfarm from a true costing perspective.

The results are reported, discussed and compared against one another and to recent qualitative studies. The chapter summary discusses the suitability of the methodology with respect to the results returned.

Finally, Chapter eight draws together the various arguments presented within this thesis, concluding on the suitability of quantifying externalities in monetary terms and their inclusion as an element within the planning of generation expansion and electricity production. Particular conclusions are drawn for the windpower generation option, while the concluding remarks address the additional issues raised within the thesis concerning externalities. Lastly, recommendations for future research are put forward and discussed.

Chapter 2

The External Costs of Fuel Cycles

2.1 The Economic Theory of External Costing

It is accepted that gaining a benefit usually involves a cost, a cost-benefit analysis determining whether the benefit is justified by the cost. The benefits of producing electricity as a distributable source of energy are readily evident, the costs involved now being the traditional costs plus various pollution (externality) impacts.

In pure economic terms the optimal level of pollution may be illustrated by considering the marginal abatement and damage cost curves (Figure 2.1). The social optimum for a particular fuel cycle exists when the marginal damage cost is in equilibrium with the marginal abatement cost, that is, when the marginal costs and benefits are equal. (Note that abatement refers to any mitigatory measure reducing damage, not exclusively gaseous abatement from fossil fuelled plant.)

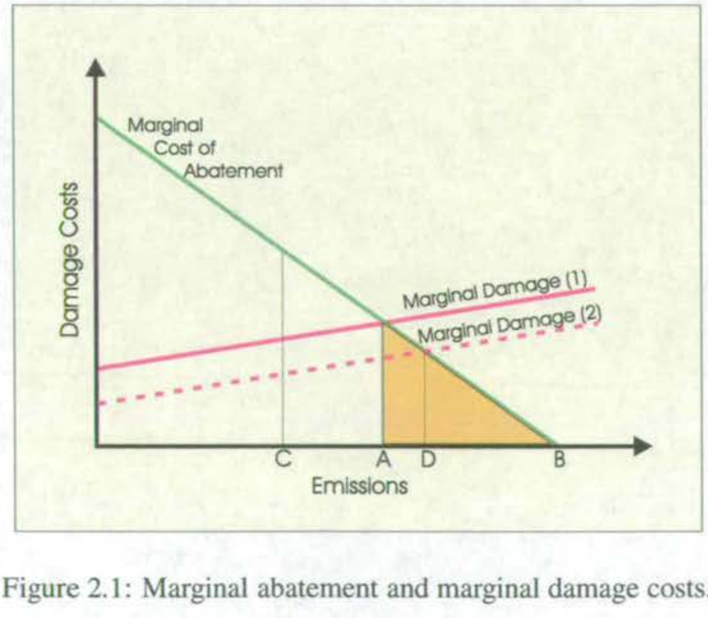

Figure 2.1: Marginal abatement and marginal damage costs.

The following summarise the points of interest in Figure 2.1:

- Point B

  No abatement procedures have been implemented, therefore high marginal damage costs result in a non-efficient allocation of resources.

- Point C

  Great emphasis has been placed on abatement producing low marginal damage costs and high marginal abatement costs, again a non-optimal allocation of resources.

- Point A

  This is the socially efficient and optimal level of pollution for this particular fuel-cycle where the marginal cost of damage and the marginal cost of abatement are at an equilibrium.

The equilibrium at A assumes that all damages including externalities have been accurately quantified, otherwise the resulting level of pollution is sub-optimal. This is illustrated by a new equilibrium at D, where the marginal damage curve (2) is reduced as certain damage costs have been ignored. This is a more accurate description of the present state of affairs within the ESI.

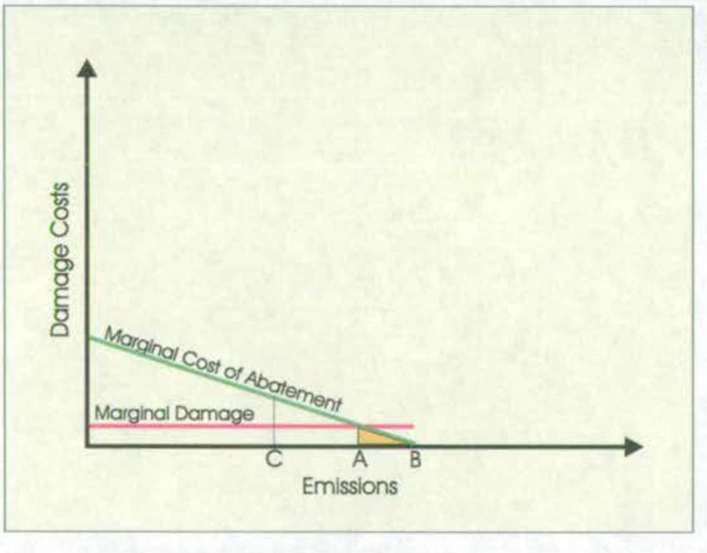

Figure 2.2: Marginal abatement and marginal damage costs for a second fuel-cycle.

Each marginal damage and abatement curve is specific to only a single fuel-cycle generation technology at a specific location. Figure 2.2 refers to a similar curve for another fuel cycle (depicted on the same axes and at the same scale as Figure 2.1), the resulting cost of the equilibrium being lower than that in Figure 2.1 and therefore an improvement over that fuel cycle.

Other associated costs and benefits (monies associated with technical feasibility, capital costs, savings in oil imports etc.) must however be incorporated with the optimal costs of abatement (or externalities) to provide the full cost-benefit scenario.

2.2 Externalities Within the ESI

There are a number of externalities existing within the generation, transmission and distribution of electricity. Figure 2.3 summarises the burdens, their impacts and the costs that form such externalities.

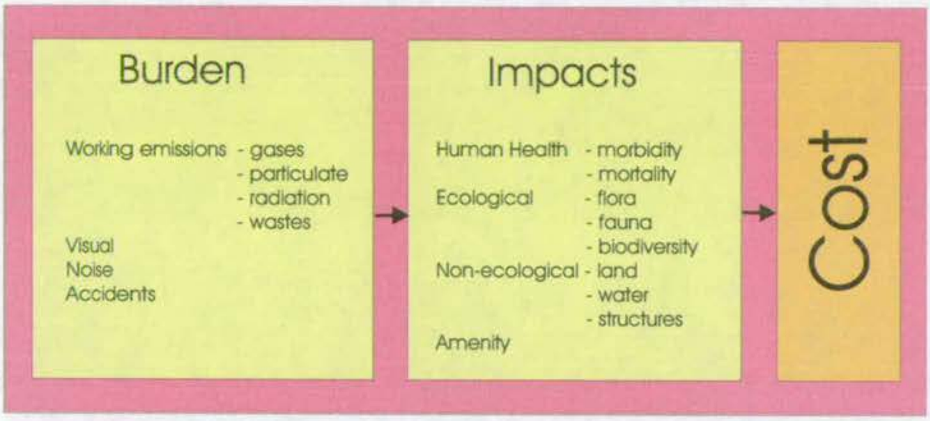

Figure 2.3: The externalities associated with electricity production.

2.2.1 ESI Market Structure and Externalities

A number of ESI structures are in existence throughout the world today. Table 2.1 summarises [5]. They range from the vertically integrated nationalised or state monopolies without direct competition, to those free of all but the minimum regulation required to promote an undistorted market mechanism providing feedback to enable optimal resource allocation.

2.2.1.1 Nationalised ESI

In a nationalised ESI the main force in determining optimal resource allocation during the planning of power system expansion is political will in consultation with various scientific, technical and economic bodies. Accounting for external costs often exists indirectly through 'criteria documents' linking mortality and morbidity to pollution levels. In such primarily qualitative evaluations between multiple factors, suboptimal allocation has been proven to arise from the lack of the invisible hand of the market, an inefficient equilibrium being reached. An example would be the often-extreme cases of pollution arising in the command economies of the old Eastern Bloc where market forces were discouraged.

Model	Features	Adoption
Vertically integrated regulated monopoly	- government regulation - franchised energy market - single entity for all functions	France Italy Spain
Unbundled monopoly	- government regulation - franchised energy market - separate distribution and generation - transmission linked to distribution or generation	Denmark Germany Holland
Unbundled limited competition	- separated generation, transmission and distribution - regulation of transmission and distribution - open access to the grid - regulation of franchise market - competition to supply large customers	Sweden Finland
Unbundled full competition	- separate generation, transmission and distribution - regulation of transmission and distribution - open access to the grid - regulation of franchise market - competition to supply all customers	Norway UK

Table 2.1: IEA utility-market characterisation models.

2.2.1.2 A Deregulated Competitive Market

In an increasing number of countries, nationalisation has been superseded by privatisation where direct regulatory oversight is diminished as far as is practical allowing free-market mechanisms to provide internalisation. Most commentators readily agree that privatisation promotes cost effectiveness, improved service, economic efficiency and somewhat cynically, significant sales revenue for the exchequer.

Although the post-privatised ESI has applied rigorous economic criteria to power station building, leading to the much publicised 'dash for gas', market forces attempting to produce an optimal resource allocation fail where externalities exist. A number of measures have been suggested and are described in Section 2.3.

Liberalisation of the ESI does not diminish the government's responsibility in those areas outside of the definition of new instruments concerned with distortions in the market mechanism. Governmental efforts must also address the issues associated with lack of incentive for innovative schemes that may later prove beneficial but require specific initial funding and encouragement. The following section details the role of the policy maker in such a market.

2.2.2 Policy, Regulation and Externalities

Policy is generally used to define objectives to which specific regulation provides a means of convergence. Policy is highly dependent on the associated government agenda and varies widely, perhaps optimistically, with the aim of providing maximum benefit to those it serves.

With regard to externalities within the ESI, regulation has been used to express a policy or preference where no other method to do so existed. For example, the US Power Plant and Industrial Fuel Use Act (1978) prohibited certain seemingly profitable activities, specifically the construction of new gas burning plant, and Holland introduced large subsidies (35% to 45%) for seemingly less profitable wind power projects. Both these regulatory measures exemplify such preferences. The resulting stimulus in the Dutch case provided 240MW or 1% of the country's electrical requirements. The former example of limiting gas burning hints at the realisation of a value in retaining a resource for the future. Inclusion of a resource value for the future, particularly for future generations, requires policy and regulation which attempt to manage a finite good effectively and at least in empathy with the interests of future generations.

Policy concerning externalities can affect how electricity is produced according to the:

- choice of fuel,
- choice of generation technology,
- value placed on renewables,

or affect how much electricity from each generation option is consumed by:

- full cost electricity pricing,
- the removal of subsidies on mature technologies.

With regard to policy instruments such as regulation a number of factors are of importance. The instrument should:

- address the externalities of significant magnitudes,
- operate at the relevant geographical scale for the impact,
- promote subsidiarity (consideration at the appropriate level of democratic hierarchy),
- address long term effects in a satisfactory manner,
- promote market change towards sustainability,
- promote a proactive attitude,

- leave room for economic optimisation,
- consist of a rational approach,
- aid commercial integration,
- provide political acceptability [6].

It must be noted that within an open market all policy actions are limited by the economic consequences they impose.

2.2.3 The Drivers for the Inclusion of Externalities

The drivers for the inclusion of externalities as identified by the European Commission [7] include:

1. the development of environmentally adjusted national accounts,
2. development of a community (European) wide cost-benefit methodology,
3. valuation of environmental assets,
4. execution of comprehensive cost-benefit analysis of all EU policies with an environmental dimension,
5. improvement of information on the state of the environment.

   To which may be added:

6. the optimal allocation of scarce resources,
7. the removal of inconsistencies within the ESI market mechanism.

2.3 Mechanisms Attempting Optimal Allocation

There have been a number of direct attempts to force marginal costs (MC) to equal marginal benefits (MB) with regard to external costs within fuel cycles. The simple objective is to remove market distortions and reach the optimal societal equilibrium in an efficient manner.

An allowable quantity of an externality (e.g. an emission) is defined according to the allowable ambient levels and future targets as derived from 'criteria documents' linking mortality and morbidity to pollution levels. Technical, economic, scientific and political agendas are normally incorporated to determine the final allowable pollutant quantity or its price. The setting of an equilibrium point is fraught with uncertainty.

There are currently a number of methods based on the 'polluter pays principle' (PPP) where charges due to the pollution are passed to the consumer. The consumer may then choose cheaper, less polluting electricity. The lack of viable clean alternatives to replace more polluting fuel-cycles is however a drawback at present. The methods used to obtain better resource allocation by the inclusion of externalities (specifically emissions) through PPP are described below and may be listed as:

1. those that are 'price based', that is, a monetary value set for the equilibrium point $(MC = MB)$:

    - fuel taxes.

    This price may unintentionally relate to a pollution quantity greater or less than the optimum.

2. Those that are 'quantity based', that is, a pollutant quantity set for the equilibrium point:

    - command and control,
    - tradable emissions permits.

3. Those that are based on market stimulation measures by means of an objective recognising the cost or benefit associated with a pollutant,

    - fossil fuel levies (government led),
    - green tariffs (consumer led),
    - customer credit (consumer led),
    - buy-down programmes (consumer led),

2.3.1 Command and Control

In 1920 Arthur Pigou [8] suggested that governments should tax pollution at the level where $MC = MB$. If a polluter's marginal cost of abatement is less than the tax the polluter will implement this saving, if higher then the tax is paid to offset damages. Command and control is based on a similar principle: invest in abatement to meet the set government externality (pollution) levels or pay a fine. Environmentalists have preferred this method as its legalism by regulation is perceived to provide the security of environmental certainty. There are however a number of drawbacks:

- economic inefficiency of costs as much as 22 times greater than those using market mechanisms [9],
- difficulty in monitoring,
- difficulty in proving overpollution,

- monetary distributional problems when industrial money is transferred to general government spending rather than to industrial investment and improvement.

An example of such a device is the European Council's Large Combustion Plant Directive (LCPD) applying to all thermal plant with a rating greater than 50MW. The specifically entailed UK reductions for SO_2 and NO_x are detailed in Table 2.2.

Target Year	SO_2	NO_x
1993	20	15
1998	40	30
2003	60	-

Table 2.2: The UK LCDP emission reductions as percentages to the 1980 base.

2.3.2 Fuel Taxes

Fuel taxes are a direct method apportioning damage costings from particular gases (CO_2, SO_2, NO_x) as an addition to the price of the fuel emitting the pollution. This methodology has proved popular in Nordic countries, for example, the Swedish (1991) CO_2 tax of 0.25 Swedish Krona per tonne on oil, natural gas, LPG and petrol [10]. The advantages are the collection of revenue at the point of sale and the continual pressure exerted by the additional cost causing convergence towards optimal allocation. The disadvantages are:

- the application to a limited number of impact pathways,
- the transfer of funds from industry to government,
- the fair application across all those causing a similar impact, for example, both power stations and internal combustion engines produce CO_2,
- the economic penalty incurred if other countries do not have such taxes and are therefore more competitive,
- the undue influence of political and economic considerations.

2.3.3 Environmental Levies

Rather than implementing a tax on fuel, a levy is placed on the good producing the externality, for example, electricity produced from fossil fuels. The levy funds are used to provide benefits directly associated with offsetting the costs of the original externality. Such schemes as the Non Fossil Fuel Obligation (NFFO: England and Wales), Scottish Renewables Order (SRO) and Northern Ireland Non Fossil Fuel Obligation (NINFFO) series provided funds for nuclear and renewables via the Fossil Fuel Levy in an attempt to reallocate the externalities unrecognised in the actual market. Regulation obligated the regional supply companies to include a percentage of electricity sourced from non-fossil fuels in their portfolio. Detailed description is included in Section 3.4.3. An 'E', or environmental externality factor to be directly added to energy pricing has also been suggested.

2.3.4 Tradable Emissions Permits

The allowable (preferably optimal) quantity of a specific pollutant is defined. Each unit of this pollutant then requires an emission allowance (EA) permit for its emission. If a polluter does not require all their EAs they may apply for an emission reduction credit (ERC) which is 'bankable' or sellable. At equilibrium, tradable permits resemble an emissions tax, the advantage of such a 'quantity' based measure being that the market price responds accordingly. An example of such a scheme is the use of tradable SO_2 permits in the US providing the basis for a market for pollution [13]. A number of features exist to implement this market successfully. 'Offsetting' requires a new or expanding source in an area already at the pollution threshold to purchase local ERCs, 'netting' allows an expanding source to use ERCs to remain at a pollution level equal to the original threshold despite a new one, and a 'bubble' aggregates and averages multiple emissions owned by the same source thereby allowing for plant differences.

Permits are initially allocated by auction which entails the perceived disadvantage of a transfer of funds away from the energy supply industry and direct mitigation to generally allocated government funds. Studies in such markets indicate a resultant shift to low sulphur coal and a dramatic fall in the cost of scrubbers due to increased economies of scale. Experience also shows that utilities have banked large amounts of ERCs, for example, 39% in 1995 [11] to allow them to continue polluting when more stringent regulations appear. The major advantages are thus:

- quantity based,
- all market sectors may participate, for example, environmentalists.

The disadvantages are:

- difficulties in policing the system, that is, monitoring and proof of over-pollution,
- regional differences, for example the cost of pollution in industrial Pittsburgh is the same as that in the Prairies,
- the initial transfer of funds to the government.

2.3.5 Green Tariffs

Alternative consumer-led methods to include external costs rely on consumer awareness of, and care for, environmental issues. For example 'green' premium price electricity tariffs guarantee that a certain proportion of the customers electricity is sourced from renewables. The premium price reflects the fact that electricity from RE is presently more expensive to produce from a traditional costing point of view, but with the addition of externalities this may no longer hold true. Green tariffs appeared because some consumers recognised the potential impact of externalities and that no direct account had been taken of them. There had been a failure of both the market mechanism (due to distortions) and the lack of any mechanism directly dealing with the externality. Reliance on altruism or voluntary self-disbenefit, although relevant in exemplifying a choice, should not be taken as a normative method or basis by which to remove a market distortion, since the risk of others capitalising on the distortion remains. Green tariffs of this kind are therefore conceptually flawed when used to 'remove' market distortions.

2.3.6 Customer Credits and Emerging Renewables Buy-down

A customer credit seeks to make allowance for the perceived benefits or externalities of using renewable energy resources by refunding some of the customers bill. For example, Californian customers utilising a non-utility source of renewable power generated in California and registered as such with the California Energy Commission are eligible to receive a 'customer credit'. (A maximum reduction of 1.5 cents per kWh, limited to a total of 1000USD per annum for the first two years.) A 'Power Content Label' describes the breakdown of the electricity by source for a particular tariff or product.

Similarly, the emerging renewables buy-down recognises the benefits of renewable technologies as compared to traditional and attempts to encourage their uptake. To achieve the desirable uptake, buy-down schemes provide direct grants to domestic consumers for the purchase of small scale renewable technologies. For example, under California's emerging renewables buy-down programme, grants for up to 50% of the total cost are available for RE technologies of less than 10kW, grid connected and utilised at a domestic level.

Both these schemes tackle the problem of external costs from basically correct economic principles. That is, the introduction of truer market mechanisms through the realisation that renewable energy is socially more beneficial than many traditional energy sources. However, the supposed or perceived value of such schemes may not be that of the social optimum.

2.3.7 Future Methods of Accounting for Externalities

Conceptually, it is possible to arrange for the trading of externalities or their associated risks. Such trade provides wealth to be invested in the production of benefits such as safety, thereby migrating to an economically optimal cost-benefit equilibrium. One example is that the estimated cost in saving an additional life per annum by investment in radiation reducing measures is 3600USD for hospital X-ray equipment and 1 billion USD for nuclear waste disposal [12]. The lower cost of measures associated with hospital X-ray equipment to produce one less death directly reflects the significantly greater risk associated. It would therefore be of much greater cost-benefit to invest in measures for hospital X-ray equipment rather than nuclear waste disposal. A resulting bilateral trading agreement in risk, decreasing the radiation risk associated with hospital X-ray machines and increasing the risk associated with nuclear waste disposal, may provide a greater social benefit overall.

2.3.8 International Issues

It is perhaps the first time in history that transboundary global effects of humankind's own making are becoming apparent. The energy industry has a large proportion of blame to shoulder in such matters. The previously mentioned techniques may now have a part to play in providing the optimal allocation of costs and benefits at a global level. Particular use is possible of internationally tradable permits. The Kyoto green-house gas protocol (Annex 1, Article 6) allows for such international trading, the exact means of which is currently under development. The main hurdles to such implementation are seen to be:

- establishing the relevant emissions quota for each country,
- high complexity of processes and systems requires considerable and dependable information,
- impartiality of administration,
- the heterogeneity of the markets in which the industries exist (monopoly - unbundled).

An example of international pseudo-trading or joint implementation already exists between Norway and Mexico, where Norway has invested in energy efficiency in Mexico with the CO_2 credit belonging to Norway, thus benefiting both countries [14].

2.3.9 Summary of Externality Control Mechanisms

Table 2.3 summarises the nature and characteristics of various mechanisms for externality incorporation or control.

A number of relevant options to remove the market distortions associated with externalities have been described. There are perceived advantages and disadvantages with each instrument or mechanism. However, independent of the chosen mechanism or associated ESI structure (direct regulatory through to full market), the attempt to realise optimal resource allocation necessitates a valuation of the fuel cycle externalities to set the equilibrium point (MC = MB) for which any instrument will aid convergence. The accurate quantification of externalities must be the basis for all such instruments.

	Regulation	Fuel Taxes	Levies	Tradable Permits	Green Tariffs	Customer Credits
Control approach	Quantity	Price	Quantity	Quantity	Price	Price
Point of control	Plant	Wholesale pricing	Regulator	Plant	Retail pricing	Retail pricing
Direct link of externality to the market	No	Yes	No	Yes	No	No
Economically efficient	No	Yes	No	Yes	No	No
Addresses long term effects	Yes	Yes	Yes	Yes	No	No
Monetary distribution problems	Yes	Yes	Yes	No	Yes	Yes
Transaction costs	No	No	No	Yes	NA	NA
Removes market imperfection	Yes	Yes	Yes	Yes	No	Yes
Limited impact pathways	No	Yes	NA	Yes	NA	NA
Influenced by temporary politics and economics	No	Yes	Yes	No	Yes	Yes
Consumer driven	No	No	No	No	Yes	Yes

Table 2.3: Summary of externality control mechanisms and the effects of various factors. (NA - Not applicable.)

2.4 Quantification of External Cost

It is argued that ignoring or undervaluing externalities results in a sub-optimal and therefore unacceptable allocation of resources to society as a whole, with often only the private polluter benefiting. Therefore a methodology to provide quantification of externalities is required.

Early studies attempting to quantify externalities used a 'top-down' or 'macro' method aggregating pollution, damage and thus cost, at a regional or national level. Lately the 'bottom-up' or 'micro' methodology has been favoured through its transparency and logical approach in quantifying externalities. Prior to the availability of large amounts of computing power such a rigorous method was not a realistic option. The 'impact pathway' approach is one such 'bottom-up' approach, and is summarised in Figure 2.4.

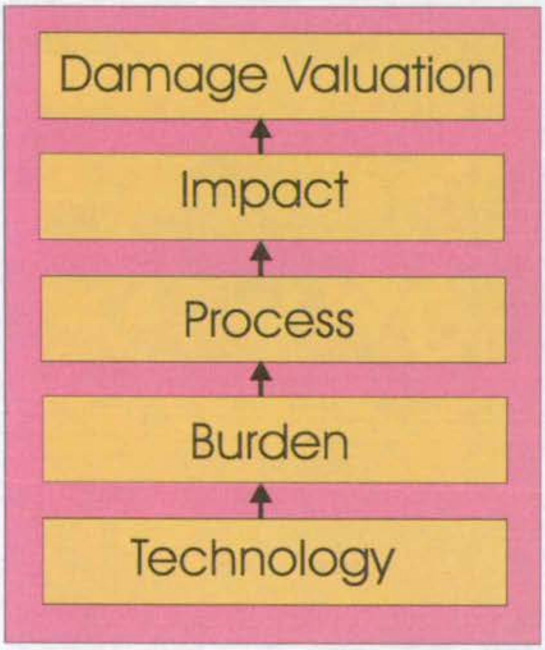

Figure 2.4: The impact pathway methodology [15].

2.4.1 Morality in the Quantification of External Cost

A number of significant moral dilemmas exist for the inclusion of normally unmarketed (often environmental) goods in any value (monetary) based market mechanism:

1. Monetarising an externality such as pollution is likely to be deemed as a positive social statement of indifference to a polluter. That is, the motive becomes that of profit maximisation rather than sound externality or environmental management. The polluting behaviour is not stigmatised.
2. The inclusion into a market system of normally unpriced but valued commodities

with which there is no previous market experience, produces erroneous valuation.

3. Wealth distribution and associated attitudes provide differing pollution responses; for example, a lower willingness to accept (WTA) payment in less developed countries than in those that are already developed.

Although these factors are valid and of cautionary importance there exist strong counter-arguments.

1. Any monetary (or quantity) value on pollution states a societal preference measure, adjustable to reflect cost and benefit.
2. Previous pollution problems were due to such valuable commodities existing outwith a market in which optimal allocation could take place.
3. Wealth is a political problem rather than an economic problem. Attitudes change with education.

It may therefore be concluded that 'if it is feasible to establish a market to implement a policy, no policy-maker can afford to do without one' [16].

2.4.2 Use Categories

In regard to externalities there exist two differing categories of resource usage.

1. Use values.
   (a) Direct use.
   The agent physically experiences the commodity in question, for example an agent loses farmland due to a new power station and thus loses the benefit associated with the crop.
   (b) Indirect use.
   This exists when the agent is indirectly affected by an impact. Continuing the previous example, the loss of a crop may affect those wishing to purchase that crop locally due to a preference for locally grown produce.
2. Non-use, passive-use, or existence value.
   These exist when even though there is no identifiable use made of the good in question an individual's value for it is still present. For example, the great concern over Antarctic wildlife by many who derive no discernible use from this good.

The major considerations when estimating valid economic values for resources entailing externalities are that

- these resources are not normally exchanged in markets with observable transactions,

- the utility derived by consumers often goes beyond direct use to non-use or passive-use values.

2.4.3 Methods for Quantifying Externalities

Of the types of 'use', direct use is often most easily quantified due to the existence of explicit markets. A direct dose-response function is often appropriate.

In many cases of direct use and all cases of indirect or passive use no direct market exists to provide valuation of the good in question. Therefore techniques outside the range of normal market valuation are required. These are categorised as those dependent on observed economic behaviour:

- hedonic pricing,
- household production functions,

and those based on elucidating an individual preference by an economic decision from which values may be deduced:

- contingent valuation.

2.4.4 Dose Response Functions

A dose-response function directly relates a 'dose' of some kind (e.g. pollution) to its 'response' and therefore monetary cost via definite pathways expressed mathematically. For example, a formula could be developed which relates increasing levels of aircraft noise near an airport to the extra cost of mitigating such noise to the original level by introducing double glazing. The basis for such valuation is therefore the definition of the physical qualities and quantities associated with the externality (by scientific experiment) to which a market value may be ascribed.

2.4.5 Hedonic Pricing

Models such as hedonic pricing relate the measurable increase or decrease in an individual's resources due to a change in some external circumstance. An example would be the reduction in the selling price of someone's house as a cement plant had been built nearby. Specific historical economic data is thus the basis for hedonic pricing.

2.4.6 Household Production Functions

Techniques valuing a change in utility such as 'averting behaviour' and 'travel cost' belong to this category. These are evaluated by observing the monetary value individuals are willing to pay to have (or not have) a certain amenity or good. For example, people are willing to pay to travel to areas where they can enjoy hill walking. Their willingness to pay (WTP) reflects the demand or value of such factors as the 'view' and 'wilderness'. Resulting valuations are based on historically observed economic behaviour.

2.4.7 Contingent Valuation

Contingent valuation (CV) is a survey based stated preference methodology. A sample of those likely to be affected by an undertaking are asked to estimate in financial terms, their WTP to have, or not to have, the undertaking, and their WTA having, or not having, the undertaking. The respondents induced economic decisions are used to infer the estimated economic valuation of the relevant non-marketed good.

2.5 Error and Uncertainty

The methods outlined in Section 2.4 have associated errors and limitations which may also lead to the sub-optimal allocation of resources. A number of difficulties common to the majority of valuation methods are clarified below.

2.5.1 Discounting

Greater value is placed on a 'good today' due to the uncertainty and risk associated with factors governing the value of a 'good tomorrow'. For example, if it were possible to pay not to have a power station nearby, many individuals would be prepared to spend more (as an average per annum) in the short-term rather than make a long-term financial commitment because of uncertainties about the future. A discount rate therefore reflects this risk and uncertainty, but also the future returns on the productive use of money invested now.

The choice of discount rate has major policy implications for resource allocation. Small changes in discount rate can result in noticeable externality valuation differences due to the often significant duration of impacts. Therefore any externality valuations must be framed by their sensitivity to discount rates.

2.5.2 Transferability

The original valuation data is specific to the area and circumstance in which it was collected. Local features merit separate valuation if accuracy is to be consistent. For example, the cash incentive to work in conditions of danger or with risk of injury is likely to be much higher in a developed country than in a less developed country. Attempts to use benefit transfer in conjunction with meta-analysis provide estimated valuations at a general level only.

2.5.3 Dependence on Historical Data

Any method depending on observed historical valuation data is specific to the time at which it was gathered. To optimise a future project involves the transfer and extrapolation of such data, inducing error.

2.5.4 Internalisation

Some externalities are already accounted for (internalised) and should not be double-counted. For example, 'danger monies' paid to workers in high risk situations to allow for the external costs or monetary risks associated.

2.5.5 Generalisation

Difficulties exist in disaggregating costs or benefits according to their source: for example, a fall in house prices due to both the creation of a waste disposal site and a local increase in unemployment. The factor producing the value change may be unassociated with the proposal in question, thus erroneously influencing the optimal state of the proposal.

2.5.6 Characteristics of Each Externality Valuation Method

The specific advantages and disadvantages for each valuation methodology are outlined in Table 2.4. A fuller discussion is later included for CV due to its applicability in areas beyond normal observational economic methods, and due to the current debate surrounding its use.

Method	Advantages	Disadvantages
Dose-Response Functions		
	transparency empirical and definite	pathway complexity is such that end result becomes inaccurate impacts may be unknown pathways may be unknown limited transferability to the use of local data
Hedonic Pricing and Household Product Functions		
	availability of valuation data	inability to disassociate non-relevant contributory impacts reliance on historical data lack of transferability
Contingent Valuation		
	locality and project specific can be tailored to avoid generalisation and internalisation no reliance on historical data methodology enables the quantification of non-use values	respondent free-riding and strategic behaviour implementation is time consuming and relatively expensive differences between WTP and WTA embedding and scope survey errors respondent reaction to an exercise of a hypothetical nature

Table 2.4: The advantages and disadvantages of the externality valuation methods.

2.5.7 Contingent Valuation

The disadvantages associated with CV methodology have often been argued as being cause to question the validity of using CV. It is perhaps because of the moral issues involved (Section 2.4.1) that the decision making to use CV (as the most common approach in obtaining estimates of economic value when passive use is included) tends to focus on beliefs about it's reliability. A number of arguments are now briefly put forward as to the suitability of CV.

2.5.7.1 Free-riding and Strategic Behaviour

Free-riding occurs if an individual decides not to pay (or not provide their full valuation) knowing that others will do so to the extent of project provision. Thereby, the overall valuation is underestimated and personal cost minimised. Strategic behaviour can take the form of free-riding or that of protest bidding, that is, use of an unrealistic valuation to affect the overall outcome. Warning that such behaviour is likely to produce a risky outcome or illegal result, respectively, discourages such action.

2.5.7.2 Differences Between WTA and WTP

Certain texts state that theoretically a rational being's WTP and WTA for the same result should be equal. In reality WTA is up to 3 times higher than WTP for the same good. Psychologists have shown people to be more concerned about loss than gain [17]. Offered the choice of receiving a benefit or incurring a cost, individuals are likely to risk a greater amount of what they do not have to receive a benefit. Many CV studies have therefore concentrated on WTP, but it should be noted that there may be very good reason for WTP and WTA differing. For example, it is not expected that the WTP for providing clean water to prevent 'x' child deaths in a less developed country would equal the WTA for the poisoning of clean water killing the same 'x' children. Certain decisions allude to a clear degradation of the status quo even though they both have a similar physical outcome.

A further factor explaining these differences is that a badly designed survey may be unable to convince respondents that they have the right to sell a collectively-owned good.

2.5.7.3 Embedding and Scope

A number of CV studies appear to lack sensitivity when attempting to value differences in scope. For example, similar valuations being returned for preserving a wilderness region independent of the size of the area being offered. Recent studies argue that this is due to bad survey design and current CV designs reject scope insensitivity at significant levels of confidence [18].

2.5.7.4 Survey Error

Errors are induced by taking a snapshot of population values and applying the result to the whole, sample size being the critical factor determining error bounds. Respondents may also wish to please the interviewer, their responses therefore reflecting the perceived preferences of the interviewer. A well trained neutral interviewer using a fair and informative questionnaire should produce a true response. Ironically most micro- and ultimately macro-economic data is derived from survey [19] yet their validity is rarely questioned on such grounds.

2.5.7.5 Hypothetical Valuations

There is clearly unfamiliarity in valuing such goods as environmental amenity due to the lack of relativity by which to judge such matters. The lack of such bases often provides 'evidence' that such a good is invaluable (clearly untrue due to its varied recognised uses) and therefore sacrosanct. The CV information must therefore provide realistic scenarios and mechanisms within a recognised context to provide a framework of links to 'knowns' and thus a realistically deduced valuation. Goods are commonly acquired with no prior experience, no economic text ever stating that such a precondition to rational decision making exists.

2.5.7.6 Summary of CV Critique

It may be concluded that CV methodology does have its draw-backs which must be carefully considered [20] [21]. It must be noted that without some form of methodology to quantify externalities such as those found in various fuel-cycles (in this case those associated with passive-use), any cost benefit analyses may be extremely misleading. The technique to quantify the externality should be that which is relevant to the type of 'use' incurred by the associated impact. Therefore it is concluded that for passive-use, valuation is required by the use of the foremost available technique (CV), careful survey design for the specific good in question being proven to provide sound valuation. Section 6.1.8 details the specifically required survey attributes.

2.6 Existing External Cost Studies

This section presents a survey of ESI external cost quantification studies. The studies mentioned have used a variety of the standard valuation methods, the inclusion of which has been dependent on relatively transparent and sound methodology as indicated by the academic and industrial community. The major studies and their findings are summarised in Table 2.5 [1].

Study	Coal	Oil	Nuclear	Gas	Hydro	Wind
ExternE	0.5 - 1.3	0.9 - 1	0.24	0.06	0.21	0.08 - 0.17
Hohmeyer	0.6 - 2.9	0.6 - 2.9	0 - 5.7	0.6 - 2.9	-	0
Pace	2.6 - 5.9	2.6 - 6.9	3	0.7 - 1	-	0 - 0.1
BPA	0.7 - 1.1	0.3	-	0.1	0.2	-
Tellus	4.5 - 10	10.3	-	6	-	-
Range	0.5 - 10	0.3 - 10.3	0.24 - 5.7	0.1 - 6	0.2 - 0.21	0 - 0.17

Table 2.5: Externality studies for various generation options derived from [22] and [23] in US cents/kWh.

The large range of externality estimations highlight the difficulty in quantifying such qualities. Even within a specific study, methodologies are only of a very general consistency. ExternE, with a reputation as perhaps the most extensive study of externalities to date, has a number of drawbacks:

1. Evaluation of only those externalities thought to constitute the major impacts in each fuel-cycle. For example, life-cycle analysis (LCA) cost is calculated for no fuel-cycle except wind, even though of significance in all fuel-cycles.

2. Evaluation of a small number of case studies in a small number of EC states has been used to produce general results which will prove unreliable in most specific cases.

Such problems go some way to explaining the large range differences even within similar fuel-cycles for externality quantification. Explanations are somewhat more difficult to come by for the seemingly low valuations of 0.24 cents/kWh for the nuclear cycle as compared to any other, and are viewed as suspect, even if only by the financial markets reluctance in supporting the floatation of the nuclear industry due to the associated risks and liabilities over huge time spans; that is, due to externalities. Evidence suggests that such broad conclusions are insensitive to the details of the technology and location of a specific power plant, and therefore to the real cost.

2.7 Summary

Externalities have been defined and their importance to social welfare noted.

Various policy and regulatory measures have been utilised in attempts to include externalities, specifically in the context of gaseous emissions. The success of all such measures rely on the basis of accurate externality quantification.

[1] The exchange rate used to convert between US Dollars and ECUs is 1:1.21.

Externality information is generally unaccounted for in traditional forms of internalisation due to a previous lack of attention and the commonly vague definitions concerning bio-physical and preference factors. A number of methods exist to quantify such external cost, reliability being dependent on careful choice of methodology to provide the appropriate valuations while remaining within acceptable error bounds.

Previous studies have intimated broad figures for external cost on a non-specific level. Such inconclusive results should not preclude their inclusion in costings or indeed invalidate the general principle of full cost welfare optimisation.

This chapter concludes that external cost is an important factor in correctly identifying the socially optimum utilisation of a fuel cycle. Further study and quantification at specific levels is required to provide greater accuracy and therefore greater welfare optimisation.

Chapter 3

UK Electricity Generation and Externalities

3.1 Introduction

Demand for electrical energy in the UK has increased since its first combined private and public utilisation, in Godalming, England, during 1888. Presently electrical energy accounts for 17% (25 MToe) of total UK energy usage [24]. Such a significant amount of electricity production is certain to entail externalities as alluded to in the previous chapter. These unallocated preferences require some mechanism for their inclusion and, normally, this relates specifically to those with national and social responsibility, namely the government and the chosen officers or bodies associated with the Electricity Supply Industry (ESI).

The status of the UK ESI with regard to planning, evaluation and inclusion of externalities must be examined in association with governmental targets and policies. All relevant ESI fuel cycle choices must be briefly appraised as to their potential to meet the UK's electricity needs, and their contribution to optimum social welfare by the incorporation of externalities. Possible implementation barriers for each generation option should be identified and thus the desirable fuel-mix relating to governmental (societal) objectives discerned.

3.2 The UK Governmental Role

Since the inception of electricity generation, the UK has played a role at the forefront of ESI development. To evaluate the level of optimal resource allocation, UK governmental policy, particularly post-privatisation, must be examined, specifically from the basis of including externalities.

The main spheres of the UK government's role regarding energy supply may be summarised as:

1. Framework setting.
   Legal rights and obligation facilitating the optimum resource exploitation according to all parties.

2. Regulation in the consumer interest.
   The provision of an energy regulator, Ofgem (previously Offer and Ofgas), discussed in Section 3.2.2.

3. Actions in the wider public interest.
   The government responsibility to ensure the sufficient supply of the energy which is fundamental to society's well-being.

3.2.1 Energy Policy

Since energy is central to economic and social activity the development of an energy policy involves diverse, complex, often contradictory factors and interests in an efficient balance to satisfy all essential objectives. The central energy policy of the UK is based on [25]:

1. security of supply,
2. diversity of supply,
3. sustainablity of supply,
4. competitive pricing of supply.

These allude to the requirement of a reliable energy supply at reasonable cost, now and in the future.

3.2.1.1 Security of Supply

Security of supply ensures that the present and future essential energy requirements are met. It also recognises that there is a cost associated with failing to supply electricity. The present UK market approximation of the 'value of lost load' is 270p/kWh [26], not including social costs. Ideally, the electricity market should optimally diversify risk, but, in practice, the electricity supplier is not normally affected by the resulting social costs as market feedback mechanisms do not normally extend to this level.

3.2.1.2 Diversity of Supply

Diversity implies the avoidance of excessive reliance on a technology, delivery route, delivery means, market structure or fuel source. Diversity thus mitigates risk and is delivered by basing decisions on calculated future levels of uncertainty regarding various energy related factors. Diversity includes fossil fuels and their alternatives in realistic proportion, and contributes to security of supply. For example, a heavy dependence on oil coupled with the oil crises in 1973 and 1980 led to greatly increased energy prices - a lack of diversity resulting in security issues.

3.2.1.3 Sustainability of Supply

Sustainability recognises the requirement to provide a better quality of life for present and future generations. Economic, social, resource and environmental factors must all be incorporated. Many fuel sources are finite in quantity and should conceptually be used in an optimally efficient manner. Nuclear energy is likely to be sustainable far into the future, while Renewable Energy (RE) is sustainable. RE is recognised by the British government as requiring special provision to encourage innovation and development. At present RE's unique contribution to sustainability and security are unreflected within the electricity market. The EC's 5th Environmental Action Programme has identified energy policy as a key factor in achieving sustainability.

3.2.1.4 Competition in Supply

In order to provide competitively priced energy the UK government has reformed the energy sector by implementing privatisation as a step towards an open and competitive market. Theoretically, the competitive market is capable of producing a responsive system underpinning both security and diversity. Privatisation aims to encourage innovation, improve efficiency and raise service standards. Benefits should also result from a social and environmental perspective. Further detail outlining privatisation of the ESI is included in Section 3.3.2.

To fulfil the roles and objectives as regards the energy industry, the UK government utilises a number of policy instruments:

- Economic instruments.
  The market is the preferred mechanism claimed to harness the ingenuity of all society as the primary instrument to attain governmental (societal) objectives.

- Direct regulation.
  The traditional governmental action, which has recently been limited to the measures required to remove market distortions and short-termism in relation to governmental objectives.

- Government support schemes.
  Direct governmental intervention to schemes perceived to be in the public interest but currently unattractive to investors.

UK primary legislation, as regards the ESI, is intended to encourage the adaptable implementation of secondary legislation through the Secretary of State, supporting electricity market development while advocating the national energy objectives via the policy instruments. In Scotland such powers are devolved to Scottish ministers. Formal consultation with the appropriate parties is likely before changes to the arrangements are implemented.

3.2.2 Role of the Regulator

Because the market formed under privatisation was regarded as imperfect, the position of Regulator was created. The Regulator has the power to apply economic instruments to attempt to prevent exploitation of such entities as the consumer and the environment. That is, the regulator moderates a private sector motivated by short-term profit.

The statutory duties of the Regulator (now Ofgem) as set out in the Electricity Act (1989) [27] and the amendments in the Competition and Service (Utilities) Act 1992 [28] are summarised as being:

- To secure that all reasonable demands for electricity are satisfied.
- To secure that licence holders are able to finance the carrying out of the activities which they are authorised by their licences to carry on.
- To promote competition in the generation and supply of electricity.

Further duties include,

- the protection of customers in terms of price and service,
- the promotion of energy efficiency,
- the promotion of research into new techniques to generate, transmit and supply electricity,
- the accounting for the effects on the physical environment of activities associated with generation, transmission and supply.

The overriding objective of regulation to date has been directly economic, those measures adopted by the Regulator having clear and profound market effects. The light-handed governmental approach has led to regulation determining energy policy by default, raising the question of who should be responsible to the public. The initial rejection of an 'E' or externality adder to the cost of energy by the regulator of gas, Ofgas (now a part of Ofgem), illustrated the regulator's reluctance to "making very serious policy decisions which are normally the role of parliament" [29]. It may be concluded that it is often unclear as to where a responsibility for an energy objective (outside of a general duty) lies, particularly in areas of complex economic worth, for example; security of supply, diversity and environmental issues.

3.2.3 Environmental Policy, Regulation and Liability

The central tenets of UK energy policy and the duties thereby placed on the Regulator make clear that energy policy must be closely linked to the consideration of the environment and therefore environmental policy. Environmental regulation is taken as the most usual method within the UK at present to deal with the most serious of the externalities existing within the ESI.

3.2.3.1 Energy Policy and Environmental Policy

Energy policy must be based on an environmental appraisal, regarding:

- policy aims,
- policy options,
- policy impacts,
- significance of the impacts,
- impact quantisation,
- cost benefit methodology,
- choice of preferred option,
- policy monitoring and evaluation.

Several environmental policies of specific current importance are concerned with: CO_2, other green house gases (GHG), NO_x and SO_2 emissions; localised environmental impacts; the development of combined heat and power (CHP) and RE.

Policy as regards these environmental externalities specifically relates to a number of primary governmental commitments and aims [30]:

- The EU legal agreement at Kyoto (Kyoto Protocol to the UN Climatic Change Convention - 1992) translates to a specific UK CO_2 emission reduction of 12.5% (below the 1990 level) between 2008 and 2012.
- UK Governments aim (1997) to reduce CO_2 emissions to 20% below the 1990 level by 2010.
- The provision of 10% of the UK's electricity from renewables by 2010.
- The UNECE Convention on Long Range Transboundary Air Pollution commits the UK to reduce SO_2 emissions by 80% compared to 1980 levels by 2010 [31].

It is noteworthy that most renewable energy is supplied as electricity. All commitments to RE must therefore be measured against the realitistic ability to incorporate large quantities of time varying electrical energy into the electrical network.

3.2.3.2 Environmental Regulation and the ESI

UK environmental regulation is addressed at both local and national levels.

Localised power station or ESI impacts are regulated by local authorities under the standard planning guidelines and regulations. The development of power stations between 20MW and 50MW capacity requires planning permission and an air pollution control permit. Power stations of over 50MW capacity require, in addition, consent from the Secretary of State, and the Environment Agency (England and Wales) or the Scottish Environmental Protection Agency (SEPA) in accordance with the Electricity Act 1989.

Integrated pollution control (IPC) is required for a new or expanding pollution source under Part 1 of the Environmental Protection Act 1990 [32]. Authorisation is given by the Environmental Agency or SEPA. IPC is based on reducing pollution to acceptable levels according to BATNEEC (best available techniques not entailing excessive cost) principles.

Public safety is detailed in the 1988 Electricity Supply Regulations and enforced by the Engineering Inspectorate of the DTI, while nuclear safety is enforced by the DTI supported by the Health and Safety Executive.

3.2.4 Influences of European Policy

Within the European Union (EU) energy context, a number of likely general policy trends in additional support of security, diversity, economic and social progress are emerging.

- The continued adoption of open and freely competitive markets.
- The internalisation of external costs in market prices, fully conforming with EC Treaty (Article 130r(2)).

3.2.4.1 Environmental Liability

Environmental liability is the product of three principles of European law relating to the concept of sustainable development:

- the "preventative principle",
- the "precautionary principle",
- the "polluter pays principle".

The UK Government has embraced these principles [33]. In future, environmental liability is likely to emerge as a major concern within environmental law. The EU's Fifth Action Programme on the Environment states:

> "Environmental liability will be an essential tool of last resort to punish despoilation of the environment... it will provide a very clear economic incentive for the management and control of risk, pollution and waste" [34].

Environmental liability is a further powerful driver towards the inclusion of externalities within fuel cycles when undertaking cost benefit analyses. The liability towards these external costs will lead to higher overall costs for the ESI in the form of more expensive capital finance and increased insurance premiums.

3.2.5 Conclusions on UK Energy Policy

Previously the inclusion of externalities has relied heavily on a top-down approach, that is, by regulation. The shift to an open electricity market has resulted in a similar shift towards efficient regulation by use of economic instruments to ensure: diversity, security, sustainability and efficient pricing. Economic instruments could displace a substantial proportion of direct regulation (within ESI related spheres of influence), minimising bureaucracy and recycling monies to the correct part of the economy. The EC has stated that this approach is preferred to a general tightening of environmental standards [35].

The Regulator as implementer between the government and industry is in a position to enforce stronger regulation factoring externalities, although appears unwilling to do so.

UK policy is increasingly affected by EU policy. With regard to externalities, UK ESI policy has not implemented direct measures even though EU policy is likely to recommend their direct inclusion in the future, not least in response to environmental liability.

The inclusion of externalities is likely to compel limitations on the nature of electricity generation.

3.3 The UK ESI Structure

The UK ESI has been through a number of significant structural changes over the past 100 years. A basic understanding of the historical and present structure of the UK ESI is a requirement in evaluating how externalities were, and may in future, be incorporated.

3.3.1 Nationalisation

The UK ESI was nationalised in 1947 and eventually formed the Central Electricity and Generating Board (CEGB) in England and Wales with 12 area boards providing distribution. Scotland comprised of the South of Scotland Electricity Board (SSEB) and the North of Scotland Hydro-Electricity Board (NSHEB) undertaking all facets of supply within their areas.

The Energy Council coordinated between the ESI and the government in setting prices and developing energy policy, inclusive of qualitative estimates concerning a small number of externalities, the majority of which related to employment, or the directly observed effects of various generation options upon health.

3.3.2 Privatisation

In 1988 the British government published a White Paper [36] announcing its intention to create a new ESI structure embracing a competitive market approach at all stages of the electricity delivery process. The bulk of the nationalised ESI was sold off during 1990 and 1991. Table 3.1 summarises the privatised companies formed in England and Wales. The two companies formed in Scotland retained their vertically integrated structures to account for such factors as the economic difficulty in supplying remote areas.

Generation	Transmission	Distribution (RECs)
National Power PowerGen	National Grid Company	Eastern Electricity East Midlands Electricity MANWEB Midlands Electricity Northern Electricity NORWEB Southern Electricity SEEBOARD South Wales Electricity South Western Electricity Yorkshire Electricity Group
Scottish Hydro-Electric Scottish Power		

Table 3.1: UK ESI at vesting: Horizontally integrated companies created in England and Wales, Scottish companies are vertically integrated.

At the time of writing, the ESI in England and Wales has been unbundled into the functions of generation, transmission and distribution. Most electricity is traded through the Pool, the National Grid Company (NGC) balancing supply and demand by scheduling plant on a half-hourly basis. The cheapest plant bid to that period is called first, more costly plant being called subsequently as required to meet total demand. All the Generators (plant operators) are paid at the Pool Purchase Price (PPP), that is, the price paid to the most expensive generator during that half-hour period (system marginal price) plus a capacity payment. Suppliers purchase the produced electricity at the PPP plus uplift, the cost of grid stability. Various contractual agreements exist between Generators and Suppliers to protect themselves during large PPP variations.

The UK has gone further than most towards the liberalisation of the ESI leading to a dynamic market-oriented scene attracting worldwide interest. Future plans to encourage further competition are presently under final consultation.

3.3.3 The New Electricity Trading Arrangements (NETA)

At the time of writing, the UK electricity market is currently seeking to separate monopoly activities from those that are competitive, thereby introducing a fully competitive supply market. The new features include:

- The separation of supply and distribution into distinct licensable entities, supply being completely competitive and distribution a closely regulated monopoly similar to transmission.
- No Supplier to have a monopoly in the supply market.
- No Supplier to retain a long term tied customer base.
- New wholesale electricity trading arrangements to replace the Pool (England and Wales), chiefly by bilateral contracts.

Figure 3.1 illustrates the proposed new ESI structure in England and Wales. The new trading arrangements for Scotland are likely to be similar. Table 3.2 summarises the market characteristics of each of the functions making up the newly structured ESI.

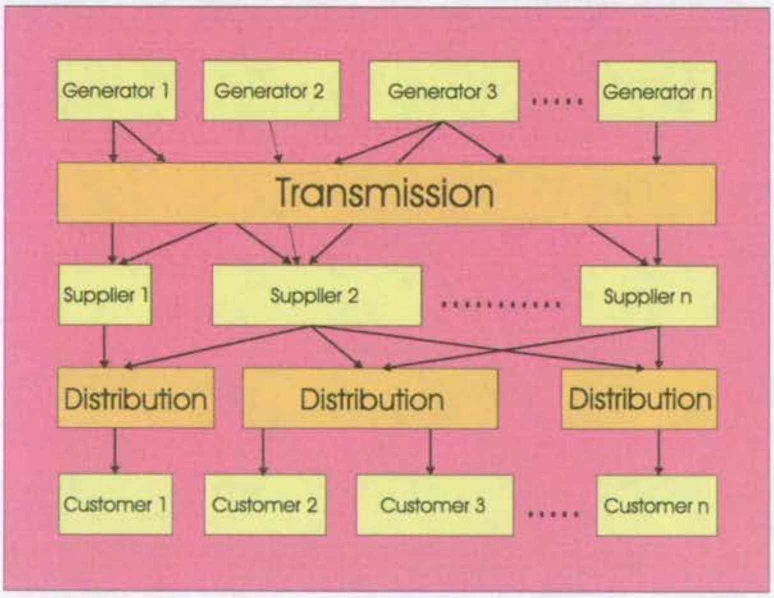

Figure 3.1: The proposed new ESI structure for England and Wales.

	Generation	Transmission	Supply	Distribution	Retail
Regulation	Unregulated	Regulated monopoly	Unregulated	Regulated monopolies	Unregulated
Pricing	Competitive	Cost-recovery	Competitive	Cost-recovery	Competitive

Table 3.2: England and Wales ESI functions under the new trading agreements.

3.4 The UK ESI: The Present Inclusion of Externalities

In line with the shift towards market mechanisms and the EU's commitment to including externalities, recognition of two broad themes have alluded to their inclusion within the UK ESI.

1. The recognition of the detrimental effects (greater external cost) caused by the emissions associated with fossil fuel combustion.
2. The recognition of the possible value of renewable energy (lesser external cost).

3.4.1 Fossil Fuel Combustion

The regulations developed under the nationalised ESI in regard to fossil fuel externalities have remained relatively unchanged in form since privatisation. Environmental standards have been gradually tightened within this regulatory framework. Section 3.2.3.1 outlines the various government agreements concerning the inclusion of some previously unaccounted for costs through the setting of emissions targets.

In terms of externalities such as environmental pollution, the UK system at present lacks any reasonable market mechanism for their direct incorporation and thus lags on these bases behind a number of systems currently in operation. Probable future measures to address these issues are presented in Section 3.4.4.

3.4.2 Renewable Energy (RE)

RE is defined as energy from sources that are regarded as continuous and infinite. Such resources are characterised by low power densities, high unpredictability, and complex collection mechanisms as compared to fossil fuels. The immature status of RE imposes a barrier to capital access and investment due to the associated higher capital costs and greater uncertainty in payback. However, the UK government recognises that renewables do provide benefits unreflected in the market price of electricity (external benefits).

The claimed advantages of renewable energy sources are that they:

- substitute valuable fossil fuels,
- represent locally available decentralised energy supply,
- are free from significant levels of pollution,
- are a means of reducing CO_2 emissions,
- contribute to energy supply diversity and security,
- displace imports and improve the balance of payments,

- financially benefit rural economies requiring inward investment.

3.4.3 NFFO, SRO and NINFFO

As previously noted, although valuable, RE generation cycles require further measures to encourage and improve their competitiveness and market penetration. In recognition, the British government implemented the Fossil Fuel Levy in conjunction with the Non Fossil Fuel Obligation (NFFO 1-5, England and Wales), Scottish Renewables Order (SRO 1-3, Scotland), and Northern Ireland Non Fossil Fuel Order (NINFFO 1-2) through the Electricity Act 1989.

These schemes aimed to provide a subsidy for renewable and nuclear energy development while encouraging electricity price convergence with conventional technologies. At convergence the renewable technology competes competitively without financial support. Figure 3.2 illustrates the convergence of prices in a downward trend for various renewable fuel cycles under NFFO [1]. This constant pressure to provide lower cost RE at levels competitive with other sources is the subsidy exit strategy.

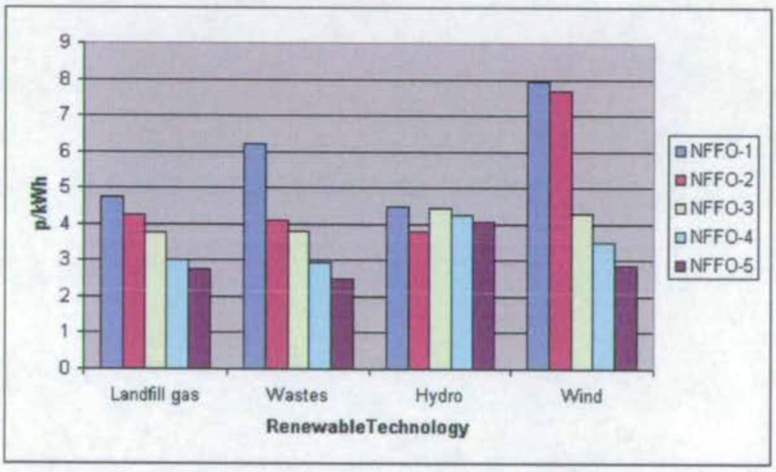

Figure 3.2: The convergence of NFFO generating costs [37].

3.4.3.1 Administration of the Fossil Fuel Levy

Renewables developers bid their proposals into each scheme, those proposals considered to be economically and technically sound (the 'will secure' test) being approved. The Public Electricity Suppliers (PES) are obligated to include a percentage of RE in their electricity portfolio. The electricity is bought at the contract price through the Non Fossil Purchasing Agency (NFPA), the difference between the reference price and the contract price being refunded to the PES from the funds created by the Fossil Fuel Levy.

[1] Average cost of successful bids, NFFO-1 and 2 data adjusted for shorter contract lengths.

The reference price is the price of electricity if it had been bought from non-renewable Generators rather than renewable, taken as the average pool selling price in England and Wales, or in Scotland, the marginal cost of production at Longannet power station. The Fossil Fuel Levy is set by OFFER on all leviable electricity (currently 0.7%) and passed on to consumers.

3.4.3.2 Success of NFFO, SRO

Table 3.3 lists some of the technologies awarded contracts under SRO-1 (1994). A large proportion of the projects (61%) remain uncommissioned 5 years later. This general characteristic is also evident for NFFO as detailed in Table 3.4 (NFFO-2) and Table 3.5 (NFFO-3). While project lead-time is one factor responsible, it is often at the planning stage that projects are delayed or rejected. This is often because of local opposition due to external costs. Therefore it should be noted that although funding is available for RE technologies, the actual implementation has been significantly below required levels. The incorporation of all costs including externalities is again alluded to (specifically at the eventual local level) for the optimal choice and siting of generation. This is discussed in depth in Chapter 4, specifically with regard to windpower.

Technology	Total Projects	MW(DNC)	Live Projects	MW(DNC)
Wind	12	45.60	7	25.13
Biomass	1	9.80	0	0.00
Hydro	15	17.25	4	3.22

Table 3.3: The current status of SRO-1 (1994) [38].

Technology	Total Projects	MW(DNC)	Live Projects	MW(DNC)
Wind	49	84.43	25	53.83
Hydro	12	10.86	10	10.46

Table 3.4: The current status of NFFO-2 (1991) [39].

Technology	Total Projects	MW(DNC)	Live Projects	MW(DNC)
Wind	55	165.63	16	41.67
Hydro	15	14.48	6	9.72

Table 3.5: The current status of NFFO-3 (1994) [39].

3.4.4 Provision for Future Inclusion of Externalities

Recognition of the need to include external costs within the UK ESI has resulted in the formation of government policy to address some select issues. Simultaneously the government wishes to drive NETA onwards to a more liberal energy market. The development and implementation of these two policy trends need not be contradictory, although it often appears disjointed in practice where the inherent short-termism of the free market conflicts with the longer term requirements of society.

There exist a number of broadly accepted UK policy options to be incorporated within NETA.

1. Energy taxes and emissions trading.
   In recognising the external costs associated with fossil fuel cycles the government has proposed a Climate Change Levy (CCL) [40]. The CCL is to be introduced after April 2001, the expected levy rate for electricity being 0.43 p/kWh [41]. 'New' forms of RE (windpower etc.) are exempt from the CCL. With reference to Figure 3.2 it is noted that inclusion of the CCL will produce significantly more competitive RE. This is discussed in Section 3.6.2.

2. Direct Grants.
   Monies have been made available through such schemes as the EC's Fifth Framework Programme for technologies requiring initial subsidy or development.

3. Obligations on the ESI to provide electricity of a lower external cost (renewables)
   The aim is to ensure lowest cost renewable energy sourcing. An obligation is to be applied to a single class to diminish market distortion (either Supply or Distribution). A number of proposed schemes exist to implement such an obligation, each with distinct advantages and disadvantages dependent on the obligated party [42]. The obligation should attempt to:

   - have no effect on overall competition,
   - allow for long term agreements (RE market stability),
   - enable market mechanisms for RE,
   - encourage initially immature technologies,
   - allow for the transfer of existing contracts.

   The majority of those being consulted favour an obligation placed on the Supplier [43]. The major difficulty encountered in assigning an obligation highlights the problems associated with including the inferred benefits of such resources as RE within a market mechanism. It is not possible at present to value consistently all externalities such as security and diversity, but a very strong argument exists to assign all known costs and benefits (including externalities) thus allowing the simple functioning of a further deregulated market.

4. The provisions for the continued funding of ongoing NFFO and SRO contracts will be dependent on the new market arrangements chosen. There is a commitment to maintain payments and investor confidence.

3.4.5 Comments on the Inclusion of Externalities

UK government policy does attempt to recognise the existence of externalities. However the specific inclusion of externalities has not *per se* been taken into account in the pricing of energy from generation options.

NFFO, SRO and NINFFO are proclaimed as having been successful in promoting longer term RE innovation, as market based mechanisms often focus on short term certainties rather than long term possibilities. It is, however, likely that the market price to which RE attempts to converge is not a true cost price if externalities were included in all fuel cycles.

A clear gap exists between government policy and the mechanisms available to achieve them both at a national and local level. For example, the externalities associated with local RE development (further discussed in Chapter 4).

The implementation of an energy tax (CCL) is to be welcomed as an initial recognition of certain externalities, the recent disassociation of RE from this tax being desirable to true costing approaches.

Further deregulation of the energy market has led to consultation for new trading arrangements. The new arrangements not only discriminate (perhaps reasonably) against renewables, but fail to account directly within the electricity market for the externalities associated with RE. The new trading arrangements are likely to have significant impact on the development of renewables.

It is acknowledged that quantifying some externalities may prove difficult, though non quantification provides sub-optimal resource allocation. The UK ESI seems set to favour complex regulation and obligation with regard to externalities, somewhat inconsistent with forming a competitive deregulated energy market.

3.5 UK Electricity Generation Options

A wide range of fuel cycle options exist for the future provision of the UK's electrical energy. The various characteristics, externalities and scope for development of each relevant fuel cycle are presented.

The historical contributions of the major fuel cycles to the supply of UK electricity are summarised in Table 3.6.

Region	Fuel Type	1970	1975	1980	1985	1990	1995	1997
England and Wales	Coal	72	67	80	66	70	46	34
	Oil	18	19	9	14	4	1	0
	Gas	0	4	0	0	0	20	30
	Nuclear	9	10	11	17	18	23	25
	Renewables	0	0	0	1	1	1	1
	Imports	0	0	0	2	8	9	9
Scotland	Coal	56	64	60	38	38	27	29
	Oil	18	8	4	14	12	0	0
	Gas	0	0	0	0	0	21	18
	Nuclear	11	9	22	35	39	42	42
	Renewables	16	15	14	13	11	10	11
	Imports	0	4	0	0	0	0	0

Table 3.6: Historical percentage of electricity generated by each major fuel cycle for the UK [71].

3.5.1 Fossil Fuels

Fossil fuels such as hydrocarbons are energy resources of a limited, irreplaceable quantity. Great use is made of such fuels due to their concentrated energy qualities, abundance within the UK and the simplicity of heat production by combustion.

3.5.1.1 Combustion Cycles and Efficiency

The combustion of such fuel produces thermal energy to raise steam which is passed through a multi-stage steam turbine that rotates an electrical generator. The greater the steam temperature drop through the turbine, the greater the efficiency. A modern Rankine, single cycle steam turbine utilising reheating and feed water preheating (steam at a sub-critical high pressure of 165 atmospheres, and temperature of 568 degrees centigrade) has an efficiency of approximately 35%. The use of supercritical pressure (250 - 300 atmospheres) and temperature (580 degrees centigrade) has attained installed efficiencies of 45%.

A combined cycle system, for example, a combined cycle gas turbine (CCGT), utilises the hot gases produced by combustion directly through a gas turbine. The hot waste gases are then used to produce steam to feed an additional steam turbine. Installed efficiencies of over 50% are common, and up to 55% possible.

Combined heat and power (CHP) uses the heat and energy derived from combustion to both generate electricity and produce heat for a specific application (for example, to meet the heat and power needs of a swimming pool, or a small community). The electrical energy produced is usually done so less efficiently than in a large thermal power station, but the overall energy efficiency including the use of 'waste' heat may approach 80%.

3.5.1.2 Coal

The UK ESI has traditionally been heavily dependent on coal due to large indigenous reserves (a peak generation dependency of 80% of all English and Welsh electrical energy in 1980, refer to Table 3.6). Coal is mined by open-cast or deep-mine methods and transported to the power station. Here it is pulverised, blown into a furnace and burnt to provide heat energy for the steam cycle.

Coal fired power stations produce large amounts of CO_2, SO_2, NO_x, ash wastes and airborne particulate matter. A typical 600MWe coal burning station with an efficiency of 30% using coal of calorific value 26 MJ/kg will theoretically produce [45]:

- 701×10^4 tonnes of CO_2 per annum.
- 3.8×10^4 tonnes of SO_2 per annum.
- 4.6×10^4 tonnes of NO_x per annum.
- 23×10^4 tonnes of ash per annum.

To meet the environmental constraints there are a number of options.

1. SO_2 abatement by flue gas desulphurisation (FGD).
   Limestone slurry (($Ca(OH)_2$) reacts with SO_2 and compressed air to form calcium sulphate (gypsum). Equations 3.1 and 3.2 describe the chemical process.

   $$Ca(OH)_2 + SO_2 = CaSO_3 + H_2O \tag{3.1}$$

   $$CaSO_3 + \frac{1}{2}O_2 + 2H_2O = CaSO_4 + 2H_2O \tag{3.2}$$

   Typically up to 95% of the SO_2 is removed in this manner, although retrofitting FGD technology is likely to increase costs by 0.3p/kWh - 0.5p/kWh at baseload. Station efficiency is lower due to the energy requirement of FGD equipment, approximately 45MW for a 4 × 500MW unit coal station [46].

2. CO_2 abatement and recovery.
   The 'clean coal' technology of integrated gas combined cycle gas turbines (IGCCGT) can remove up to 90% of the associated CO_2. A mixture of coal and

limestone are gasified in the presence of oxygen and steam in a pressurised vessel. In comparison to conventional gas CCGT, CO_2 emissions are doubled.

A number of possible methods exist to recover and dispose of CO_2.

- Amine absorption and stripping,
- molecular sieves,
- refrigeration,
- sea water absorption,
- potassium carbonate absorption and stripping.

Each method has theoretical CO_2 removal efficiencies of 90%, however, no large scale demonstration is available and costs are likely to be significant.

3. NO_x abatement.
   A number of measures have been implemented resulting in a 50% reduction of UK NO_x emissions since 1990. Measures include:

   - the use of low NO_x burners,
   - gas over-burn,
   - selective catalytic reduction (SCR).

   In future a 'clean coal' technology such as fluidised bed combustion (FBC) may be utilised. Air is injected to agitate particles of ash or sand at the combustion chamber bed, these particles providing the turbulence to maintain the ignited fuel at an even temperature. The lower combustion temperatures decreasing NO_x emissions.

4. Airborne particulate matter.
   The use of electrostatic precipitators (ESP) or wet scrubbers removes up to 99% of particulate, the collected ash being sold or disposed of.

The costs of abating these impacts, coupled with rising coal prices, and the use of less efficient single cycle generation technologies has resulted in coal becoming less competitive than gas CCGT technology. No 'clean coal' technology has been demonstrated in a large unit size, the probable end-cost being uneconomic at present. The UK DTI 'does not regard the funding of such schemes as constituting value for money' [47]. Table 3.7 summarises the major externalities associated with the coal fuel cycle.

Category	Burden	Impact	Damage Cost/Scale	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	L	G	L
	SO_2	Environment	L	T	L
	NO_x	Environment	L	T	L
	Particulates	Health	M	Lo	L
	Wastes	Environment	M	Lo	M
	Radiation	Health	S	Lo	L
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	L	R	L
Noise	C, O and M	Acoustic	M	Lo	M
	Operation	EMI on RF	S	Lo	S
Land	Presence	Sterilisation	M	Lo	L
	C, O and M	Erosion	M	Lo	L
	Fuel extraction	Stability	M	Lo	L
Local Ecology	C, O and M	Flora	L	Lo	L
	C, O and M	Fauna	L	Lo	L
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public	M	Lo	S
	Major accident	Society	S	Lo	S
	Major accident	Environment	M	R	M
Decommissioning	Wastes	Environment	M	Lo	L

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.7: Externalities for the coal generation option. (Derived: [48], [49].)

3.5.1.3 Oil

The electricity generation process from oil utilises a steam cycle, the heat being produced through the combustion of the vapourised (by a high temperature and pressure) heavy fuel oil. Oil generation has been progressively phased out within the UK ESI due to increasing oil prices since the oil price crash in 1973. Oil fired power stations currently account for no UK electricity production. It is currently uneconomic to burn indigenous supplies of North Sea oil in UK power stations. Table 3.8 summarises the externalities associated with the oil fuel cycle.

3.5.1.4 Gas

Natural gas is pumped from a (North Sea) gas field through a pipeline to the power station. The gas is passed to a gas turbine and combusted in a combustion chamber with a continuous supply of compressed air. The resulting hot gases drive the turbine blades to provide motive power to both a generator and the compressor. This is termed an open cycle gas turbine (OCGT). In a combined cycle gas turbine (CCGT) the hot 'waste' gases subsequently heating water to fuel a subsequent steam cycle. Figure 3.3 illustrates the CCGT technology.

Since privatisation there has been rapid expansion of gas-fired electricity generation using CCGT technology. Table 3.6 notes the UK fuel-mix over the past 27 years. The

Category	Burden	Impact	Damage Cost	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	L	G	L
	SO_2	Environment	L	T	L
	NO_x	Environment	L	T	L
	Particulates	Health	M	Lo	L
	Wastes	Environment	M	Lo	M
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	M	Lo	L
Noise	C, O and M	Acoustic	M	Lo	M
	Operation	EMI on RF	S	Lo	S
Land	Presence	Sterilisation	M	L	L
	C, O and M	Erosion	M	Lo	L
	Fuel extraction	Stability	M	Lo	L
Local Ecology	C, O and M	Flora	L	Lo	L
	C, O and M	Fauna	L	Lo	L
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public	M	Lo	S
	Major accident	Society	M	Lo	S
	Major accident	Environment	L	R	L
Decommissioning	Wastes	Environment	M	Lo	L

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.8: Externalities for the oil generation option. (Derived: [48], [52].)

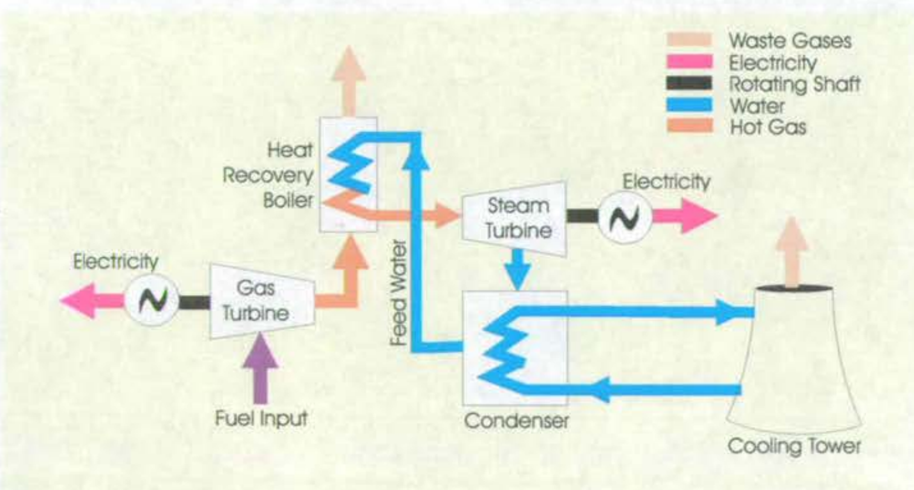

Figure 3.3: A combined (CCGT) cycle gas turbine.

discovery of large quantities of North Sea gas, the low capital cost of CCGTs and the rapid payback of such highly efficient plants provide an attractive investment in the de-regulated ESI, as indicated by the current usage. CO_2 emissions from gas generation are the least significant of any fossil-fuel combustion technology.

UK gas reserves are projected to last 18 - 28 years (including reserves and projected future discoveries) [50] at the present rate of usage. Gas is also an important feedstock for industrial chemicals. However, gas generation of electricity generation is likely to continue expanding in the near future with an effect on both diversity and security. In the longer term (post 2020) other fuel options are likely to be required to replace gas. Table 3.9 summarises the externalities associated with the gas fuel cycle.

Category	Burden	Impact	Damage Cost/Scale	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	M	G	L
	SO_2	Environment	S	T	L
	NO_x	Environment	S	T	L
	Particulates	Health	S	Lo	L
	Wastes	Environment	0	0	0
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	S	Lo	L
Noise	C, O and M	Acoustic	M	Lo	M
	Operation	EMI on RF	S	Lo	S
Land	Presence	Sterilisation	M	Lo	L
	C, O and M	Erosion	M	Lo	L
	Fuel extraction	Stability	S	Lo	L
Local Ecology	C, O and M	Flora	S	Lo	M
	C, O and M	Fauna	S	Lo	M
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public	M	Lo	S
	Major accident	Society	S	Lo	S
	Major accident	Environment	S	Lo	S
Decommissioning	Wastes	Environment	S	Lo	L

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium
S - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.9: Externalities for the gas generation option. (Derived: [48], [52].)

3.5.2 Nuclear

Fission takes place when a neutron collides with a fission fuel nucleus (usually Uranium-235), producing further neutrons, heat and two 'fission products' containing broadly equal amounts of protons and neutrons. Within a nuclear reactor a moderator (such as carbon or hydrogen) slows down the resulting neutrons to encourage further fission with the uranium, in a chain reaction. The rate of reaction is kept sub-critical by neutron absorbing boron control rods. The vast amounts of nuclear energy available by fission from small amounts of uranium or plutonium fuel produce electricity via a steam cycle and contribute large proportions of the electricity supplied within the UK (42% in Scotland, refer to Table 3.6). Nuclear power has distinct advantages over traditional fossil-fuel plant due to the small amount of fuel required (1 gramme of plutonium yielding energy equivalent to approximately 2 tonnes of coal), the ability to reprocess uranium thereby recycling up to 96% of the original fuel, the displacement of fossil fuel imports and the emission of practically no gases.

Category	Burden	Impact	Damage Cost/Scale	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	S	G	M
	SO_2	Environment	0	0	0
	NO_x	Environment	0	0	0
	Particulates	Health	0	0	0
	Wastes	Environment	L	Lo	L
	Radiation	Health	S	Lo	L
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	0	0	0
Noise	C, O and M	Acoustic	M	Lo	M
	Operation	EMI on RF	S	Lo	S
Land	Presence	Sterilisation	M	Lo	L
	C, O and M	Erosion	M	Lo	L
	Fuel extraction	Stability	M	Lo	L
Local Ecology	C, O and M	Flora	M	Lo	M
	C, O and M	Fauna	M	Lo	M
Health and Safety	C, O and M	Occupational	M	Lo	L
	C, O and M	Public	M	Lo	L
	Major accident	Society	L	G	L
	Major accident	Environment	L	G	L
Decommissioning	Wastes	Environment	L	Lo	L

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.10: Externalities for the nuclear generation option. (Derived: [48], [53].)

Calder Hall (Cumbria, 1956) was the world's first industrial scale nuclear power station. Although there are well-publicised health concerns regarding nuclear plant, it should be noted that the UK nuclear industry contributes approximately 0.01% of the UK's annual radiation dosage. There is at present no proven linkage between radiation doses from any UK reactor or reprocessing plant [39] to leukaemia or other forms of cancer.

The development of nuclear power is, however, capital-intensive due to the complexity of safety measures and the development of relatively new technology. It is also controversial due to the various perceived radiation and public health risks (fission products and risk of uncontrolled chain reaction), while waste and decommissioning present further problems. Table 3.10 summarises the externalities associated with the nuclear (fission) fuel cycle.

3.5.3 Renewables

Only those technologies deemed practical by the existence of at least one successfully generating prototype within Europe and with possible application to the UK are included in this section. Table 3.11 summarises the possibilities and the available UK resources.

Resource	Gross Potential (TWh/a) [56]	Percentage Exploited	Additional Contribution by 2010 [57]	Average Unit Peak Output (MW) [58]	Technical Maturity [60]	Commercial Maturity [60]
Large hydro	6.9	48*	1	30	5	5
Small hydro	0.6	48*	2	3	5	5
Onshore wind	318	0.2	4	0.6	4	4
Offshore wind	100**	0	3	1	2	2
Biomass (Crop)	187	1	3	9 [59]	3	4
Biomass (Waste)	283	0	3	9[59]	4	4
Wastes	13.5	8	3	16 [59]	5	4
Photovoltaic	19	0	2	0.05	4	3
Wave	700	0	1	?	1	1
Tidal	40	0	2	240	5	5

Key:
* - All hydro exploitation.
** - Developable offshore wind according to allowable seabed depth.
Potential additional contribution - **1:** Small potential, **2:** Moderate potential, **3:** High potential, **4:** Excellent potential.
Technical maturity - **1:** Experimental, **2:** Demonstration, **3:** Major improvements expected, **4:** Minor improvements expected, **5:** Little scope for improvement.
Commercial Maturity - **1:** Experimental, **2:** Demonstration, **3:** Initial commercialisation, **4:** <10 years commercial, **5:** >10 years commercial.

Table 3.11: The UK's utilised and potential renewable resources. (Current UK demand is 300TWh/annum [82].)

3.5.3.1 Hydro

Electricity is produced using the potential energy available in water as it drops between two points, the kinetic energy associated with such a flow also contributing. A water turbine rotates an electrical generator producing electricity. Hydro power is non-polluting, has an inherently long lifespan, and is of high value in providing system stability and reaction to rapid changes in electrical demand, often by the use of pumped storage. The UK has 1.35GW (Scotland 1.22GW) of installed large hydro (>10MW) capacity with a further 83MW of small hydro. This accounts for 2% of the UK's installed generation capacity. Hydro is a well established generation option exploitable at a competitive price although the economically justifiable remaining resource may be small in the UK. Further development of small-scale hydro for a part of the remaining resource is a possibility.

The major limitations associated with hydro power are the flooding of land, silting behind reservoirs, visual amenity, damburst and the ecological consequences (e.g. fish migration and disease vectors). Financial payback times are long due to the initially large capital cost.

Table 3.12 summarises the externalities associated with the large hydro fuel cycle.

Category	Burden	Impact	Damage Cost/Scale	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	0	0	0
	SO_2	Environment	0	0	0
	NO_x	Environment	0	0	0
	Particulates	Health	0	0	0
	Wastes	Environment	0	0	0
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	0	0	0
Noise	C, O and M	Acoustic	S	Lo	M
	Operation	EMI on RF	0	0	0
Land	Presence	Sterilisation	L	Lo	L
	C, O and M	Erosion	L	Lo	L
	Fuel extraction	Stability	M	Lo	L
Local Ecology	C, O and M	Flora	M	Lo	M
	C, O and M	Fauna	M	Lo	M
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public injury	S	Lo	S
	Major accident	Society	M	Lo	S
	Major accident	Environment	M	Lo	S
Decommissioning	Wastes	Environment	M	Lo	L

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.12: Externalities for the large hydro generation option. (Derived: [48], [62].)

3.5.3.2 Solar

The sun's energy may be captured by photovoltaic (PV) or solar-thermal means.

PV technology produces electricity directly from solar radiation by utilising semiconductor material (monomulticrystalline or amorphous silicon of 1 - 250 microns thickness) in which free electrons (current) flow as a result of being knocked out of the atomic bonds by photons. The maximum efficiency to date is 18% [54], equating to approximately 75 $\mathrm{kWh/m^2/year}$ with an average UK incident solar radiation of 900 $\mathrm{kWh/m^2/year}$ [55]. To date such efficiencies and the associated cost of PV technology has led to their adoption in specialised situations, for example, remote stand-alone power sources for habitation, telecommunication, navigation, instrumentation and cathodic protection.

Solar-thermal relies on a liquid or body designed to absorb thermal radiation. Although most solar-thermal is not used for electricity production, the heat captured may be transferred to a liquid medium such as water which can then produce electricity by a steam boiler, turbine, and electrical generator arrangement. Various large scale schemes (France and Spain) have been attempted in which either independent devices track the sun, or a large number of mirrors (heliostats) track the sun and reflect the incident radiation to a common point on a boiler. Fixed solar-thermal has been used in the UK to provide domestic hot water heating, however the large scale production of electricity by such means is unlikely.

The drawbacks of both PV and solar-thermal schemes include their use during daylight only, a high investment and long payback, land sterilisation, visual intrusion and the large amounts of energy and materials required during manufacture. Energy saving schemes are generally more cost effective although the recent use of PV panelling as cladding for buildings at a similar cost to normal cladding methods (after accounting for the cost of energy saved) has provided further penetration within the UK.

Table 3.13 summarises the externalities associated with the solar fuel cycle.

Category	Burden	Impact	Damage Cost	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	0	0	0
	SO_2	Environment	0	0	0
	NO_x	Environment	0	0	0
	Particulates	Health	0	0	0
	Wastes	Environment	0	0	0
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	S	Lo	M
	Pollution	Air quality	0	0	0
Noise	C, O and M	Acoustic	0	0	0
	Operation	EMI on RF	S	Lo	S
Land	Presence	Sterilisation	M	Lo	L
	C, O and M	Erosion	S	Lo	M
	Fuel extraction	Stability	0	0	0
Local Ecology	C, O and M	Flora	S	Lo	S
	C, O and M	Fauna	S	Lo	S
Health and Safety	C, O and M	Occupational	S	Lo	S
	C, O and M	Public	S	Lo	S
	Major accident	Society	0	0	0
	Major accident	Environment	0	0	0
Decommissioning	Wastes	Environment	M	R	M

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.13: Externalities for the solar generation option. (Derived: [48])

3.5.3.3 Biomass

Energy from biomass essentially uses the chemical energy captured in plant material by photosynthesis as a fuel. The two distinct generation options utilised are energy crops and waste biomass.

A fast growing energy crop such as willow is planted in copices which are harvested in rotation. Such fuel is CO_2 neutral, with that absorbed during the plant's life being released at combustion. In the UK land put out of production due to the Common Agricultural Policy (CAP) may be used to provide benefit to the farming community by such a scheme. These drier lignin rich fuels may be used in a normal combustion process or by the more energy efficient conversions of gasification and pyrolysis. The latter two methods provide a fuel directly utiliseable in combustion engines (methanol or ethanol).

Wastes biomass includes sewage and plant matter. These are processed via anaerobic digestion to produce gas, normally methane, which may be burnt to provide power through an engine or turbine. In most cases this gas would be naturally emitted by default to the atmosphere as a GHG. Therefore use is made of a pollutant to displace other pollutants (fossil fuel emissions). For example, Thetford power station (UK) produces 38.5MW from 430,000 tonnes of poultry litter per annum.

Biomass contribution is envisaged as significant although the ecological impacts due to the emission of particulates and small concentrations of SO_2 are yet to be determined.

Table 3.14 summarises the externalities associated with the biomass fuel cycle.

Category	Burden	Impact	Damage Cost	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	N	G	L
	SO_2	Environment	S	T	M
	NO_x	Environment	S	T	M
	Particulates	Health	M	Lo	L
	Wastes	Environment	M	Lo	M
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	M	Lo	L
Noise	C, O and M	Acoustic	M	Lo	M
	Operation	EMI on RF	0	0	0
Land	Presence	Sterilisation	M	Lo	M
	C, O and M	Erosion	S	Lo	S
	Fuel extraction	Stability	S	Lo	S
Local Ecology	C, O and M	Flora	M	Lo	M
	C, O and M	Fauna	M	Lo	M
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public	S	Lo	S
	Major accident	Society	0	0	0
	Major accident	Environment	0	0	0
Decommissioning	Wastes	Environment	S	Lo	S

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium
N - Neutral **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.14: Externalities for the biomass generation option. (Derived: [48])

3.5.3.4 Wastes

Wastes can include a mixture of fossil fuel, plant matter, chemicals, and combustibles. Such waste presents an environmental problem but also a possible energy source by either landfill gas utilisation or mass-burn incineration.

Landfill accounts for 90% of UK waste disposal, large quantities of combustible methane being produced in the absence of oxygen as natural decomposition occurs. Burning the methane avoids the significant environmental consequences of its release to the atmosphere, the 10.7 MW Brogborough landfill site power station being an example of a typical scheme.

An example of mass-burn incineration is the Tyseley power station (awarded an NFFO-3 licence) in Birmingham utilising 350,000 tonnes of local waste per annum to produce 25MW and 16,000 tonnes of recycled ferous metal. Incineration can cause local problems with the release of heavy metals and dioxins.

Subsidy for waste utilisation schemes has been withdrawn post NFFO-3 reflecting the technologies maturity and the incentives created by current land-fill taxation.

Table 3.15 summarises the externalities associated with the waste fuel cycle.

Category	Burden	Impact	Damage Cost	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	M	G	L
	SO_2	Environment	M	T	L
	NO_x	Environment	M	T	L
	Particulates	Health	M	Lo	L
	Wastes	Environment	S	Lo	M
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	M	Lo	L
Noise	C, O and M	Acoustic	M	Lo	M
	Operation	EMI on RF	S	Lo	S
Land	Presence	Sterilisation	M	Lo	L
	C, O and M	Erosion	S	Lo	S
	Fuel extraction	Stability	0	0	0
Local Ecology	C, O and M	Flora	M	Lo	L
	C, O and M	Fauna	M	Lo	L
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public	S	Lo	S
	Major accident	Society	S	Lo	S
	Major accident	Environment	S	Lo	S
Decommissioning	Wastes	Environment	M	Lo	L

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.15: Externalities for the wastes generation option. (Derived: [48])

3.5.3.5 Wind

Solar radiation heating effects produce motion in the earth's atmosphere delivering an estimated $2.2 - 3.7 \times 10^7$ TWh/annum [61] of kinetic energy in the form of wind worldwide. Approximately 1% of solar energy is converted to wind. Vertical (Darrius) or horizontal wind turbines are used to convert this kinetic energy into rotary torque to drive a generator and produce electrical power. The UK has the greatest wind potential within Europe, although the cost effectiveness is highly site specific depending on wind resource factors and the local supporting infrastructure. The main advantages are the relatively low price for remote stand-alone applications, quick installation time, local distribution network reinforcement, high correlation of the UK wind and demand patterns, displacement of fossil-fuel emissions (Table 3.16) and small (reversible) direct physical environmental impacts. Disadvantages relate to the complexity of a time-varying resource, the remoteness of suitable areas, the higher cost as compared to fossil-fuel generation, impact on local amenity, network stability problems and their intensive use of the landscape.

Emission	Displaced emissions (g/kWh)	Annual saving (tonnes)
Carbon dioxide	734	2200
Sulphur dioxide	10	30
Nitrogen oxides	3	10

Table 3.16: Emissions savings for a 1MW wind turbine relative to the average UK plant mix [64].

Offshore wind has been suggested as a means of circumventing many of the onshore problems, but problems remain with cabling, foundations and the creation of possible navigational hazards. Danish studies suggest that offshore wind may cost 0.04 - 0.05USD/kWh (approximately 2.6 - 3.2p/kWh) while Dutch and Swedish experience suggests that offshore wind is 50% to 100% more expensive than a similar onshore project [63]. Table 3.17 summarises the externalities associated with the wind fuel cycle.

Category	Burden	Impact	Damage Cost	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	0	0	0
	SO_2	Environment	0	0	0
	NO_x	Environment	0	0	0
	Particulates	Health	0	0	0
	Wastes	Environment	0	0	0
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	0	0	0
Noise	C, O and M	Acoustic	S	Lo	M
	Operation	EMI on RF	S	Lo	S
Land	Presence	Sterilisation	S	Lo	S
	C, O and M	Erosion	S	Lo	S
	Fuel extraction	Stability	0	0	0
Local Ecology	C, O and M	Flora	0	0	0
	C, O and M	Fauna	S	Lo	S
Health and Safety	C, O and M	Occupational	S	Lo	S
	C, O and M	Public	S	Lo	S
	Major accident	Public	0	0	0
	Major accident	Environment	0	0	0
Decommissioning	Wastes	Environment	0	0	0

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium
S - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.17: Externalities for the wind generation option. (Derived: [48] and [62])

3.5.3.6 Wave

Wave energy is the byproduct of wind acting on the sea surface, dependent on the wind-speed and the length over which the wind can act. Approximately 1% of wind energy is converted to wave energy. The Atlantic coasts of western Europe receive a large amount of wave energy. Wave devices attempt to absorb the energy in the wave, and may be categorised as shore based and offshore.

Shore based devices successfully contribute small amounts of power to the grid. The 80kW oscillating water column on Islay (Inner Hebrides, Scotland) makes use of a uni-directional Wells turbine, while Tapchan (Norway) utilises a tapered channel to raise water into a pool, the water subsequently flowing back to the sea through a turbine. Such schemes require cliff areas and a small tidal range, their drawbacks being the destruction or alteration of coastlines and the imposition of structures on wilderness areas. Widespread use of such devices in the UK is currently not envisaged.

A single commercial offshore (more correctly near-shore) device has been developed. The Osprey (1MW) was sited off the Scottish coast at Dounreay (due to grid access at the Dounreay nuclear plant) before breaking up due to damage incurred during installation. This project highlighted the problems associated with structures in the sea, particularly regarding breakup in storm weather and the problems of connection to the transmission grid. Further difficulties are the ecological effects of reducing the seas wave content and those relating to the creation of a navigational hazard for shipping.

Table 3.18 summarises the externalities associated with the wave-power (near/off-shore) fuel cycle.

Category	Burden	Impact	Damage Cost	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	0	0	0
	SO_2	Environment	0	0	0
	NO_x	Environment	0	0	0
	Particulates	Health	0	0	0
	Wastes	Environment	0	0	0
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	0	0	0
	Pollution	Air quality	0	0	0
Noise	C, O and M	Acoustic	0	0	0
	Operation	EMI on RF	0	0	0
Land	Presence	Sterilisation	0	0	0
	C, O and M	Erosion	S	Lo	L
	Fuel extraction	Stability	0	0	0
Local Ecology	C, O and M	Flora	0	0	0
	C, O and M	Fauna	S	Lo	S
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public	S	Lo	S
	Major accident	Public	M	Lo	S
	Major accident	Environment	S	Lo	S
Decommissioning	Wastes	Environment	S	Lo	S

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium **S** - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.18: Externalities for the wave (near/off-shore) generation option. (Derived: [48])

3.5.3.7 Tidal

Tidal energy utilises the regular change in sea-level (tides) caused by the gravitational attraction of the moon and sun on the oceans of the rotating earth. A high tidal range may be utilised by placing a barrage across an estuary and channelling the resultant flow through hydro turbines to generate electricity.

The west coast of England and Wales is particularly suited to such schemes, for example, the Severn Estuary could provide 8640MW [65] from the 11m tidal range. Major drawbacks include ecological damage due to the change in tidal regime behind the barrage, concentration of pollution behind the barrage, visual impact of the stored water, difficulties for migrating fish, and the provision of locks to restore shipping routes.

Table 3.19 summarises the externalities associated with the tidal-power fuel cycle.

Category	Burden	Impact	Damage Cost	Range	Cost to Mitigate
Working Emissions	CO_2	Climate	0	0	0
	SO_2	Environment	0	0	0
	NO_x	Environment	0	0	0
	Particulates	Health	0	0	0
	Wastes	Environment	0	0	0
	Radiation	Health	0	0	0
Visual	Presence	Aesthetics	L	Lo	L
	Pollution	Air quality	0	0	0
Noise	C, O and M	Acoustic	S	Lo	M
	Operation	EMI on RF	0	0	0
Land	Presence	Sterilisation	0	0	0
	C, O and M	Erosion	S	Lo	L
	Fuel extraction	Stability	0	0	0
Local Ecology	C, O and M	Flora	M	Lo	M
	C, O and M	Fauna	M	Lo	M
Health and Safety	C, O and M	Occupational	M	Lo	S
	C, O and M	Public	S	Lo	S
	Major accident	Public	S	Lo	S
	Major accident	Environment	S	Lo	S
Decommissioning	Wastes	Environment	M	Lo	L

Key: **C, O and M** - Construction, Operation and Maintenance; **L** - Large **M** - Medium
S - Small **G** - Global **T** - Transboundary **R** - Regional **Lo** - Local.

Table 3.19: Externalities for the tidal generation option. (Derived: [48])

3.6 Likely Fuel Cycle Contribution

Together the fuel cycles set out in Section 3.5 will meet the electrical energy needs of the UK during the next 20 years and beyond. Their likely individual contributions to energy supply will be dependent on various economic and political factors. This chapter has alluded to the aspects envisaged to effect the fuel mix for electricity production over the next 20 years, namely, market forces and externalities.

3.6.1 Contribution of Fossil Fuels and Nuclear

Indigenous coal reserves now prove more costly than those imported from overseas. The UK coal industry has therefore required public subsidies and preferential supply contracts. There are currently no plans for further coal power stations, although it is likely that coal will continue to produce a substantial proportion of UK electricity generation needs in the near future. Current government thinking recognises that coal presents a meaningful option and should not be lost. Although all externalities should be included in any evaluation, it is noted that emissions are the prime external barrier to further development. The increased implementation of emissions limiting measures is foreseen, therefore increasing costs. 'Clean coal' technologies require significant development and are unlikely to contribute to electricity supply in the near term.

Oil is presently uneconomic for use in power stations. Development or expansion of oil fired plant is not envisaged in the near or medium term.

Further significant contribution from gas-fired CCGT technology is likely as illustrated in Figure 3.4.

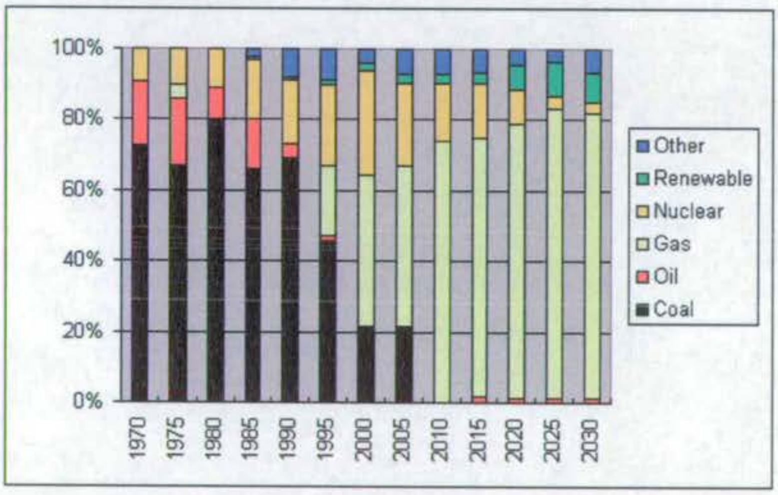

Figure 3.4: The likely contributions to UK electricity demand according to a market led scenario using the ETSU Markal Model [69].

To the present, the expansion of gas-fired electricity generation has contributed to the UK ESIs diversity of supply. Estimates suggest that 19GW of gas capacity is currently being commissioned, under construction, or consented to. That is, 15% of current system capacity. In future diversity is likely to be decreased by the projected development figures (see Figure 3.5) for CCGT expansion. If an unconstrained gas scenario is adopted, it is likely that by 2020 up to 90% of gas requirements will be met by imports [66], initially from Norway and subsequently from further afield (Russian States, Turkey and Morocco). The external cost associated with the risk of relying too heavily on a single fuel source is likely to be a barrier to UK gas fired power stations continuing to be developed at the present rate.

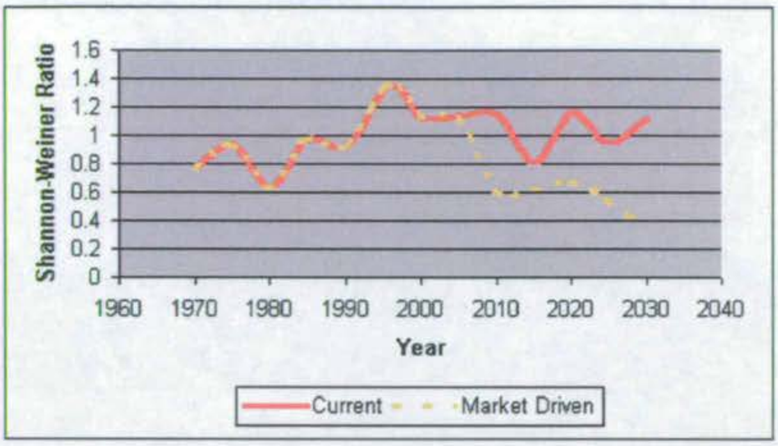

Figure 3.5: The UK electricity source diversity as measured by the Shannon-Weiner Index [70] if current policies continue and under market control. (For 6 Fuel Cycles: Coal, Nuclear, Oil, Gas, Renewable, Other and Imports - maximum diversity would be an index of 1.8)

The development of nuclear power does not presently appear economic and has therefore been curtailed in the UK. Future use of nuclear power is currently dependent on the success of life extension programmes. It is likely that up to two-thirds of the UKs nuclear stations will retire by 2012 [67], therefore nuclear power within the UK is set to diminish in the medium term.

3.6.2 Contribution of Renewables

In the near term (to 2010), the likely RE contributors to UK energy needs are: hydro, wind, biomass and wastes. Solar energy within the UK is likely to be a useful part-needs contributor for specific tasks at the point of consumption. Wave and tidal power are unlikely to be implemented in the medium term due to technological (and commercial) immaturity and the associated development problems respectively.

The government states that regulatory incentives will be required to improve RE penetration. "Technologies which would be considered as prime candidates to receive market stimulation in the UK are those most likely to be able to contribute in the near or medium term, up to 2010" [72].

The further contribution of energy from hydro is limited by the remaining resource, while energy from waste (mass-burn) is limited by the waste available. Thus the RE resources of wind and biomass remain as the realistically viable options to produce large amounts of renewable energy up to 2010.

The DTI estimated resource cost curves for renewables in Figure 3.6 reinforce this argument [71]. This illustrates the potential penetration of RE in TWh according to the cost of the electricity produced (p/kWh), enabling a cost comparison with other generation options and therefore the likely generation mix.

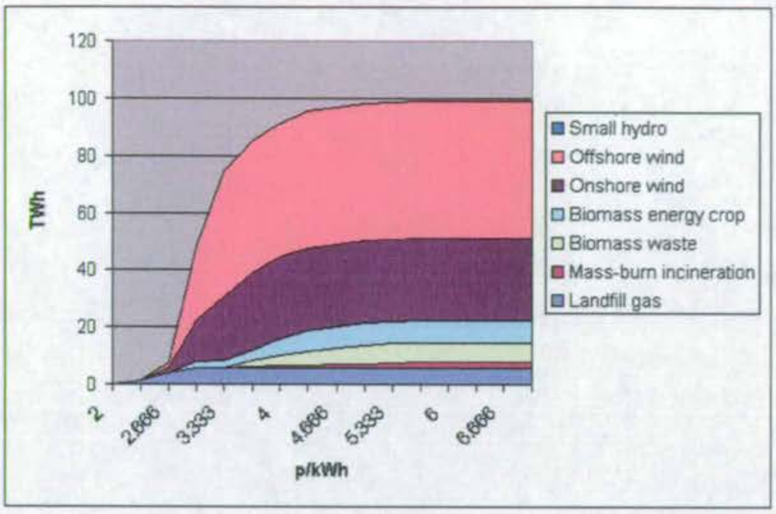

Figure 3.6: Renewable energy resource cost curve for 2010 (15% discount rate).

Table 3.20 refers to the estimated generation costs for various electricity generation fuel cycles. The demand weighted average UK Pool Purchase Price for 1998/99 was 2.62p/kWh [79]. This would indicate that the profitable new plant in an open market (without subsidy but including present levies) is currently: gas (CCGT) or energy from waste. This correlates with the present trend in power station construction.

Technology	Straight Cost (p/kWh)	Required Abatement (p/kWh)	Climate Change Levy (p/kWh)	Current Cost (p/kWh)	ExternE (p/kWh)	Total Including ExternE [77] (p/kWh)
Coal	2.3 - 2.75 [73]	0.3 - 0.5 [73]	0.43	3.03 - 3.68	0.34	2.94 - 3.59
Oil (CC)	NE	NE	0.43	NE	0.64	NE
Gas (CCGT)	1.8 - 2.2 [73]	0	0.43	2.23 - 2.63	0.04	1.84 - 2.24
Nuclear	3.39 - 3.84 [74]	0	0	3.39 - 3.84	0.15	3.54 - 3.99
Hydro	4.1 [75]	0	0	4.1	0.14	4.24
Wind	2.9 [75]	0	0	2.9	0.053	2.953
Energy from Waste	2.4 [76]	0	0	2.4	-	-
Landfill Gas	2.7 [76]	0	0	2.7	-	-

Table 3.20: Current cost for new generation plant in the UK (NE: Not currently economic [78]).

It is clear that on a straight 'traditional' costing basis RE will remain a less attractive option compared to CCGT for at least the foreseeable future. However, with the inclusion of the Climate Change Levy (CCL) of 0.43p/kWh and the introduction of tradeable "green credits" to meet government RE targets, RE investment is much more competitive. However, harnessing much of the remaining but outlying RE resource may prove less economically viable than that already utilised as indicated in Figure 3.6.

It is notable that for the coal and gas fuel cycles the CCL is higher than the estimated damage costs attributed by ExternE. The final column of Table 3.20 displays the overall cost with the incorporation of ExternE for each fuel cycle. Previous studies of externalities do, however, record greater damage values than ExternE for most fuel cycles (Section 2.6).

3.6.2.1 RE Penetration With the Inclusion of Externalities

RE plants are small, numerous, and often sited in undeveloped areas where the resource occurs. The well defined procedures for dealing with planning consents for the traditional power plants do not apply under these circumstances. The siting of RE (particularly wind and hydro) has created controversy due to the externalities involved and is discussed in the next chapter. Further quantification of these externalities is required if a strategic approach to RE provision is to be successful within a public and regional planning context. The government readily admits that *widespread adoption of renewable sources of energy will not be possible unless the public is prepared to accept projects in their locality [68].*

Incorporation of external costs (by levy or otherwise) is likely to prove that RE can compete cost effectively with other fuel cycles and therefore supply a larger proportion of electricity demand than at present. Refer to Table 3.20

Figure 3.7 refers to the probable penetration of RE technologies to the year 2010 within the EU. The inclusion of externalities to all fuel cycles illustrates the dramatic effect on the possible provision of energy from renewable resources, a 38% increase in the total percentage of primary energy over the base case.

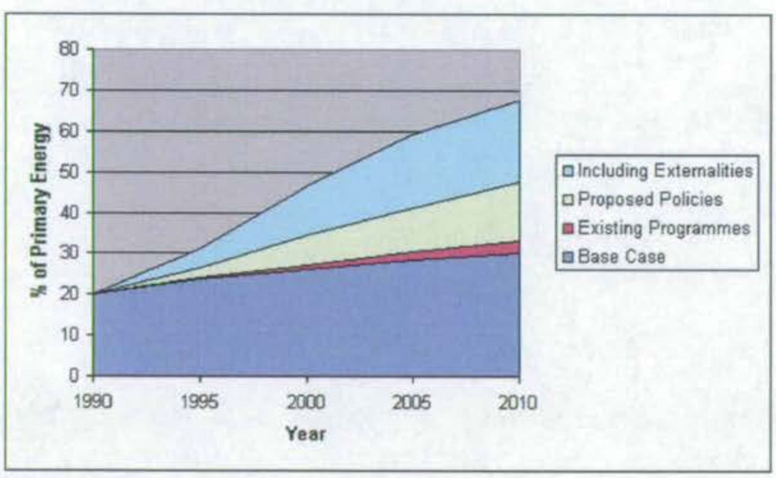

Figure 3.7: The potential contribution of RE to European primary energy supply [80].

Recent work utilising a genetic algorithm to predict the likely contribution of various generation methods to the UK electricity demand over the next 35 years has included the ExternE externality costs in a scenario [81]. Figure 3.8 depicts the output of this simulation.

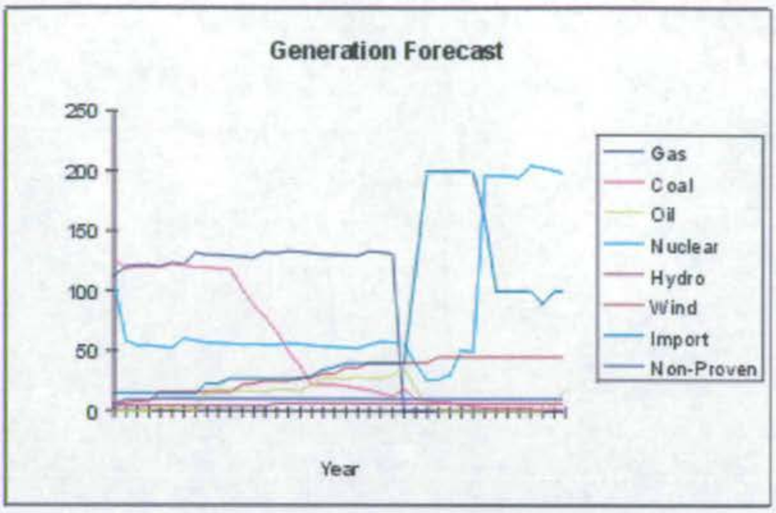

Figure 3.8: The future UK electricity generation mix (in TWh per annum) beginning at 1995 with the inclusion of externalities from year 10.

It is interesting to note the resulting shift to imported electricity, and the growth in RE contribution under such a scenario. A reliance on imported electricity is unlikely due to security considerations and the probable inclusion at source of the externalities on the generation option producing this energy. However, this simulation, although coarse in nature, reaffirms that the fuel mix when accounting for externalities would differ significantly from that otherwise predicted without their inclusion.

It has been suggested that it is desirable to include externalities for socially optimum resource allocation. Such an action in the UK ESI significantly alters the viability of particular fuel cycles and places an emphasis on the inclusion of renewables.

3.7 Summary

Governmental policy is to react to national or international environmental targets. There is no clear policy of attempted welfare optimisation by the quantitative inclusion of externalities, even at a local level.

The role of the energy regulator (Ofgem) is pivotal to the implementation of environmental policy, although it seems that there is an area between the government and regulator in which the responsibility for broader environmental issues and objectives becomes vague.

To date the application of market mechanisms addressing the distortions produced by externalities within the UK ESI have been limited to broad non-discriminatory fuel taxes, imposed measures such as the CCL and government subsidy.

Those targets defined by government policy are unlikely to succeed in an optimal manner without due regulation and a recognition of externalities within a market context.

It is claimed that the NFFO, SRO, and NINFFO schemes have successfully encouraged downward pressure on RE costs, prices 'converging' towards those of conventional technologies. It is also clear that a large number of projects are incomplete due to unaccounted for externalities, a lack of coordinated planning, and an absence of leadership.

It is unclear as to how the new trading arrangements will effect the inclusion of externalities. The apparent rush to increase liberalisation of the electricity market should not be at the expense of ignoring market distortions requiring regulation or preferably, economic instruments.

A large number of relevant generation options exist to meet the future UK electricity demand, their utilisation being dependent on the existing infrastructure, government policy, and the inclusion of externalities.

RE is likely to contribute increased amounts of energy in the UK ESI, leading to meeting the targets for security, diversity and sustainability. The extent of the contribution will be dependent on the specific full-price costing of all fuel cycles.

No consistent methodology or long term strategy is evident with regard to including externalities in the UK ESI. Measures are selected as they become necessary, or when it is evident something is amiss; that is, by a top down approach. All costs are ultimately derived where they impact; that is, at a specific locality or entity. Therefore a bottom-up approach to externalities is preferable and should be developed.

A generation option undergoing particular difficulties with regard to previously unquantified externalities (wind) is chosen to demonstrate the development of a bottom-up methodology to incorporate such costs in the planning process at a local level.

Chapter 4

Wind Energy

4.1 Introduction

Previous discussion alluded to a requirement for true costing techniques when evaluating the optimal generation mix at national and local levels. The development of a true costing model for an example generation option, wind energy, is described along with the associated design and siting requirements. Predicted project success is based on a financial appraisal defining cost, revenue and a desired return (dependent on project risk). These parameters may be purely economic or societal and are usually measured in financial terms. Aside from traditional and external cost features, financial return on a wind power development is dependent on a number of uncertainties:

- wind resource risk (mitigatable by careful siting),
- technological risk,
- power purchase price risk,
- political risk.

The later two risks are normally out-with the developer's direct control and are briefly examined in relation to a number of national policies currently implemented. This defines the basis for the subsequent description of all other cost factors for a specific project.

4.1.1 History of Modern Wind Power Development

Worldwide production of wind generated electricity has increased from practically zero pre-1980 to a current installed capacity estimated at 13400MW [86]. Present day wind developments were initiated in California during the early 1980's as a direct result of the Public Utilities Regulatory Policies Act (PURPA) requiring a fair market for Independent Power Producers (IPPs), cheap land, energetic winds, favourable investment climate, good power purchase rates, cooperative utilities, the world energy situation and federal tax credits of 25%.

California's 30 year contracts (first 10 years fixed) [83] lowered risk and encouraged financial investment [1]. A series of set template contracts between utilities and Independent Electricity Producers developed by the California Public Utility Commission (PUC) facilitated efficient contractual agreement.

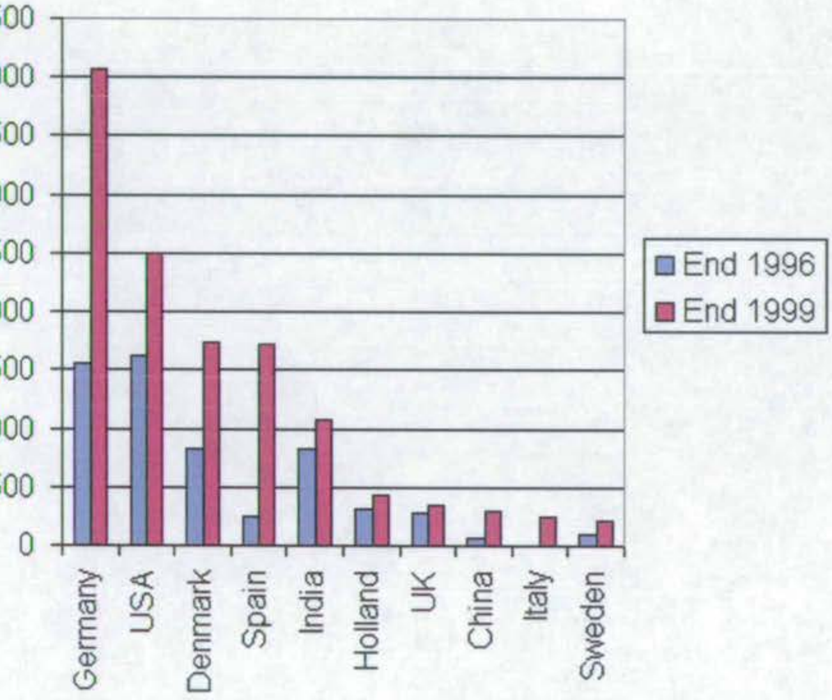

Figure 4.1: Installed wind capacity (MW), top 10 countries in 1999.

Europe has rapidly caught up the Californian lead in wind power development. Figure 4.1 illustrates the installed worldwide wind power capacity by country [85], [86]. European incentives for wind energy began in the late 1980's. The EC Alterner programme (1992) had a target of 8000MW of wind energy by 2005 (already met). The Alterner II Community Strategy and Action Plan (1998 - 2002) sets a specific target of an added 10,000MW of large wind farm capability [84]. A number of trends within Europe have emerged and are best illustrated by reference to Denmark or Germany, and the UK.

Both Denmark and Germany have politically accepted the inclusion of wind power as an essential part of their national energy policy. Consistent provision is made for supporting

[1] Fixed contracts are often favoured versus time varying non-contracted prices even at significantly lower price to the possible average time varying non-contracted price due to concerns over risk.

wind power development by setting the price for electricity generated in such a manner to 85% of the average retail rate in Denmark and 90% of the average retail rate in Germany. Electricity tax and carbon dioxide tax offsets may also be applied in Denmark, while the Germans have further specific regional incentives. Thus financial risk has been reduced by consistent national policy resulting in attractive 10-12 year loans for 60-80% of the installed cost. Contractual agreements in Denmark are relaxed reflecting the faith of financial institutions in the stability of government policy.

These fairly straightforward development features have encouraged small local developers to invest in wind technology. The majority of Danish developments are single medium sized wind turbine generators (WTGs) owned by a community cooperative. Local external costs have been nullified partly due to local involvement and thus acceptance by the institution of local plans for the inclusion of wind power as appropriate. WTGs are thus an accepted rural landuse in Denmark.

4.1.1.1 UK Utilisation

The UK benefits from the greatest wind resource in Europe (Figure 4.2 [87]). Unlike its European counterparts the UK has not incorporated a specific wind energy objective within the national energy policy. Rather, the various renewables obligations (NFFO, SRO, NINFFO) have attempted to award preferential contracts to the most cost effective renewable technologies, some allowance being made for demonstration technologies. The objective is to encourage convergence to the point where renewable technologies can compete unassisted against conventional fuel cycles. There is indeed evidence of such convergence (see Section 3.4.3), however there are drawbacks associated with such a policy, particularly in the case of wind energy.

1. The NFFO process is highly competitive, the developer of the cheapest workable proposal succeeding. This has encouraged developers to seek out the best wind resources which predominantly coincide with those upland areas most desirable from a public amenity point of view. Costly failed proposals and public ill-will have resulted.

2. The NFFO process is legalistic, resource intensive and cumbersome. The associated expense has precluded all but the most persistent of local and community developers, and encouraged the selection of prestige sites in contradiction with local amenity features in order to maintain the necessary financial returns to the developer.

3. Initial tranches retained a very short fixed power purchase price contract. For example, NFFO 1 and 2 retained a fixed power purchase price until 1998. A developer having negotiated the previous two drawbacks could hope to begin generating in 1992 leaving six years of certain income with which to repay all financial loans. NFFO 3 remedied this problem with a 15 year fixed contract, the resulting

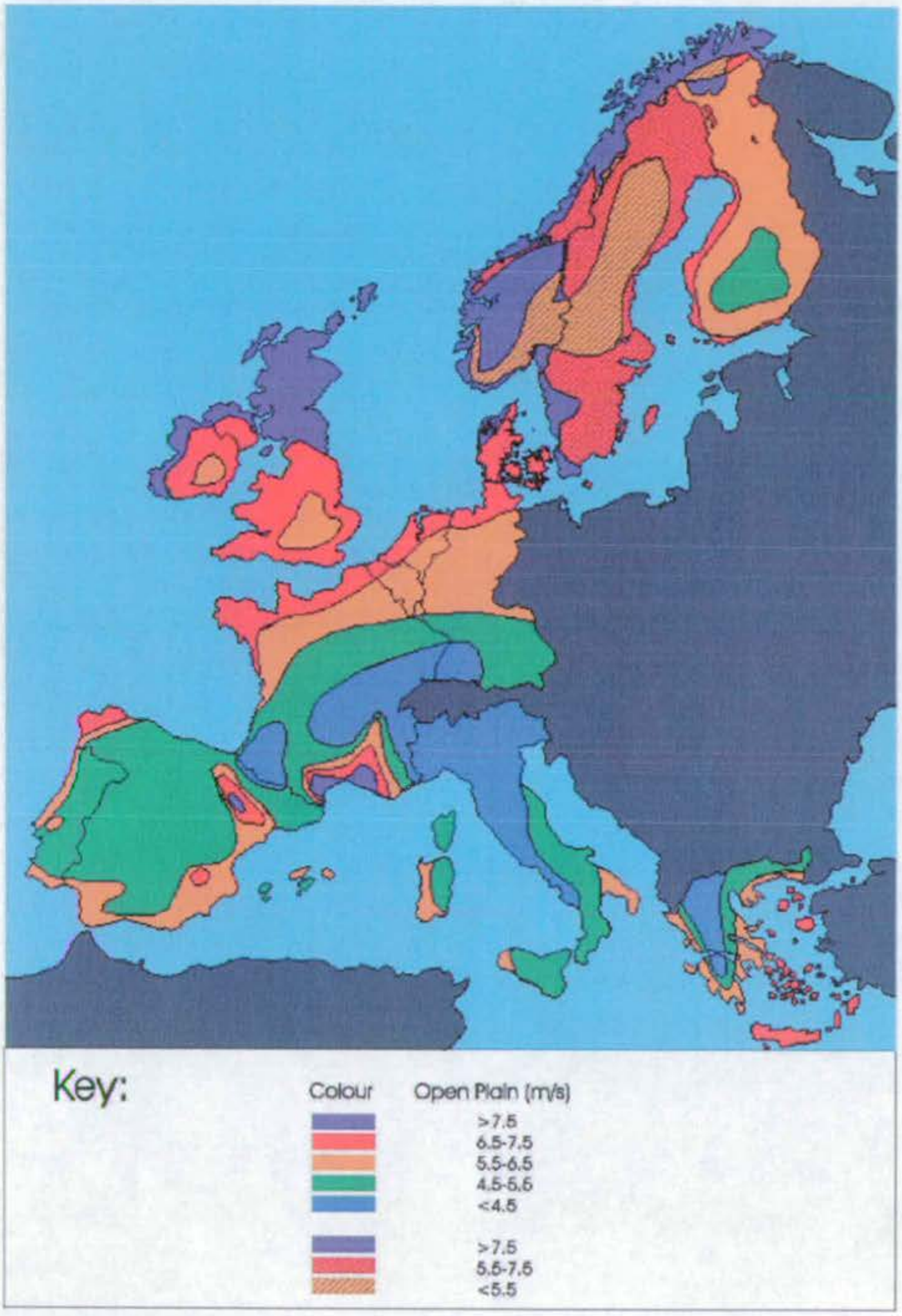

Figure 4.2: The generalised European wind resource (50m above ground).

cost of wind energy output being halved in part due to the associated mitigation of the financial risk.

Partly for these reasons, an average wind velocity of 7ms^{-1} or greater is required in the UK to produce a good return on investment in comparison to Denmark where a wind velocity of $5 - 6.5\text{ms}^{-1}$ is sufficient [88]. The uptake of wind energy for Denmark and the UK is illustrated in Figure 4.3.

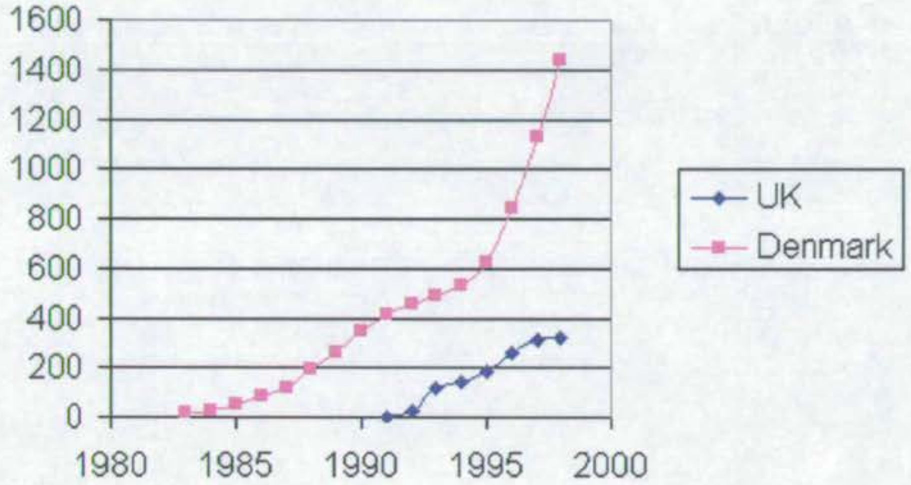

Figure 4.3: Installed Wind Capacity (MW) for the UK and Denmark 1983 - 1998. Derived from [89], [90].

Outside of the national political factors influencing the penetration of wind energy, its development within the UK generation mix has been under-utilised due to external costs at the specific level of local implementation. A possible framework forming the basis for measuring and mitigating these costs is argued. Although the form of national implementation has exacerbated a reluctance towards wind energy uptake within the UK (in comparison to other European countries), at a local level anywhere in Europe difficulties exist due to external costs.

4.1.2 Trends in Wind Power Technology

Figure 4.4 refers to the trends in WTG technology since 1984. It is clear that there has been rapid development in this sector concerning output and efficiency. In terms of reliability, present WTGs are available for 98% of the year. The layout of multiple WTGs or wind-farms is site dependent and no particular trend is evident. It is, however, more efficient to install a smaller number of large WTGs, rather than many smaller WTGs.

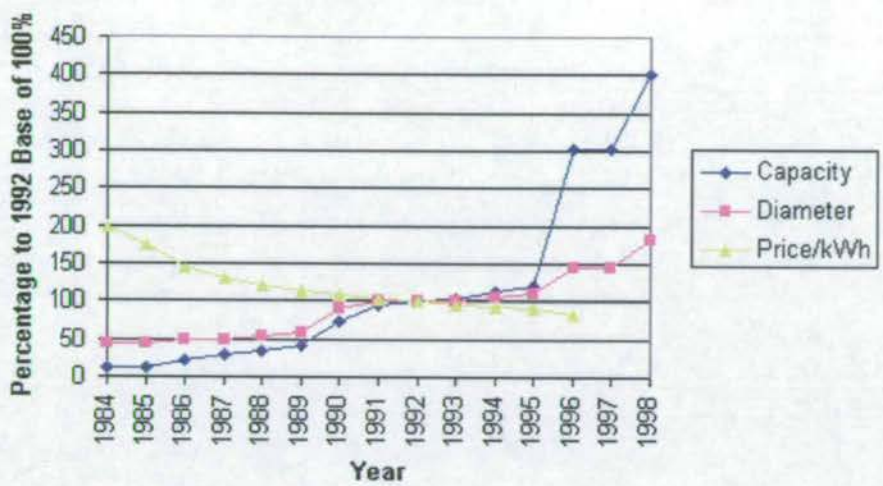

Figure 4.4: Development indicators of commercial WTGs 1984 - 1998 [91]. In 1992 the average capacity was 550kW and the diameter was 34m.

4.1.3 Wind Energy Requirements

The requirements for the siting of a single WTG or a large wind farm are broadly related although larger developments require extra planning associated with the interactions between WTGs, and the added external costs associated with scale. The initial traditional siting requirements may be outlined as:

1. sufficient wind at a sufficient speed distribution,
2. proximity to an electrical connection,
3. proximity to road access,
4. non conflict with past, present or future landuse,
5. favourable economic parameters and climate,
6. suitability of ground for construction works.

The initial concern of the developer must be the economic evaluation of possible development sites according to the critical parameter of potential energy yield.

4.2 Energy in the Wind

Wind is the resulting mass transfer of air between two points induced by a thermal gradient. A WTG makes use of this energy by the reaction upon the aerofoil blades, which induces a rotary motion transferred via the interconnecting shaft and gearbox to an electrical generator (usually a 3-phase induction machine). The equations determining the wind velocity at the WTG and the subsequent electrical output are introduced in this section. These equations are used throughout this study and the software described later.

The 'fuel' is the mass of air passing through the WTG blades. The kinetic energy possessed by such a mass 'm' at velocity 'v' is described as:

$$E = \frac{1}{2}mv^2 \tag{4.1}$$

4.2.1 Atmospheric Effects on Wind Energy

The mass of the air varies according to four factors: temperature, pressure, altitude, and moisture content. These parameters are intrinsically linked. Equation 4.2 describes the change in pressure with temperature and altitude:

$$P_r = P_{ro}\, exp\left(\frac{-(z_r - z_{ro})}{\frac{R_g.T}{g}}\right) \tag{4.2}$$

where P_r is the new pressure, P_{ro} is the original pressure, z_r and z_{ro} are the new and original altitudes respectively, R_g is the specific gas constant for air, T is the temperature and g is the gravitational constant. Equation 4.3 derives the air density (ρ):

$$\rho = \frac{P_r}{R_g.T} \tag{4.3}$$

The volume of air passing through the turbine rotor is dependent on the velocity of the air (wind velocity) and the rotor area. The mass is calculated from the volume (D is the WTG rotor diameter) and density which when substituted into the original energy equation yields:

$$E = \frac{1}{2}\rho\pi\left(\frac{D}{2}\right)^2 v^3 \tag{4.4}$$

According to Betz Law the theoretical limit of efficiency in converting the kinetic energy in the wind to mechanical energy utilising a wind turbine is 59% [92]. In terms of energy per second or power (P):

$$P = \frac{1}{2}\rho\pi\left(\frac{D}{2}\right)^2 v^3 \times 0.59 \tag{4.5}$$

For dry air at standard pressure (sea-level) and temperature of 15°C, $\rho = 1.225\text{kg.m}^{-3}$. For a rotor area of 1m^2 the power convertible (Equation 4.5) for wind velocities of 5m.s^{-1} and 10m.s^{-1} is respectively 42.2 W and 361.4 W.

4.2.2 Wind Turbine Wake Effects

Figure 4.5 illustrates the effect of wind turbine wake caused by other turbines in an array. Under wind conditions where the velocity is below the power rejection level the area where reduction in power is caused by an upwind WTG may be considered as the part of the wake cone projected on the swept area of the downwind WTG. Above the power rejection level there is little wake effect as extra energy is retained in the wind to minimise the wake [93].

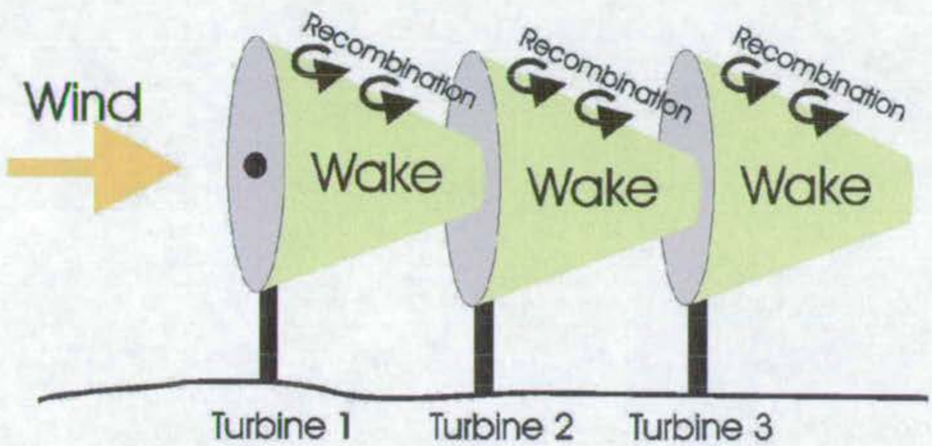

Figure 4.5: The effect of Wind Shadow within an array of turbines

The wake is made up of three distinct regions at various distances (x) as defined in [94].

- Near wake region, x $<=$ 5D
- Intermediate wake region, 5D $<=$ x $<$ 15D
- Far wake region, x $>$ 15D

The centreline wind velocity decay (ΔU_m) behind a WTG is described by Equation 4.6 where n is the exponent for the specific wake region.

$$\Delta U_m \propto x^{-n} \tag{4.6}$$

The wake width (b) is calculated by using Equation 4.7 where R is the WTG rotor radius, and m is the initial WTG wake velocity ratio.

$$b = R\sqrt{\frac{1 - 1/m^2}{4\Delta U_m[9/70 - \Delta U_m/15]}} \tag{4.7}$$

Equation 4.8 defines the radial velocity profile function ($f(r)$) within the intermediate and far wake regions where r is the radial distance from the WTG axis.

$$f(r) = [1 - (r/b)^{1.5}]^2 \tag{4.8}$$

The sum of the squares of the individual velocity deficits is calculated resulting in a small but systematic overestimate of the overall velocity deficit [95].

4.2.3 Topographical Effects on Wind

Topography, including man-made structures, affects specific local wind speed and therefore the energy available. Three main pathways for wind resource modification exist.

1. Shelter.
2. Roughness.
3. Orography.

4.2.3.1 Shelter and Wind Shadow

Obstacles such as buildings, trees and hedges create barriers to wind. The turbulent air in the lee of such an obstacle eventually recombining with free flowing air masses to regain the average wind velocity. The effect of siting a turbine in an area so affected is to decrease the available wind velocity and hence recoverable energy. The action of turbulence also degrades turbine components by fatigue. An expression for wind velocity change due to semi infinite obstacles such as walls is described in Equations 4.9 and 4.10 [96].

$$\frac{\Delta v}{v} = 9.8\left(\frac{z_{meas}}{z_{obs}}\right)^{0.14}\left(\frac{x_d}{z_{obs}}\right).\left(1 - \varrho\right).\tau exp^{(-0.67\tau^{1.5})} \tag{4.9}$$

Where Δv is the change in wind velocity, z_{meas} is the height of the original wind velocity measurement, z_{obs} is the obstacle height, x_d is the downstream distance to the obstacle, ϱ is the obstacle porosity, $rlen$ is the roughness length and

$$\tau = \left(\frac{z_{obs}}{z_{meas}}\right).\left(\frac{0.32}{ln\frac{z_{obs}}{rlen}}.\frac{x_d}{z_{obs}}\right)^{-0.47} \tag{4.10}$$

4.2.3.2 Roughness and Windshear

Roughness may be described as the collective effect of terrain surface on wind retardation. The locally available wind velocity at turbine hub-height is dependent on the effect of turbulence induced by ground roughness. This effect lessens as height above the ground is increased, and is known as windshear.

The European Wind Atlas defines a number of roughness classes each referring to a roughness length. For example, a roughness length of 0.0024 (short grass, roughness class 0.5) equates to the height in metres above 'ground' (or obstacle) at which the wind velocity is theoretically zero [97].

$$W = \frac{ln\left(\frac{rlen_b}{rlen_{selected}}\right)}{ln\left(\frac{rlen_b}{rlen_a}\right)} \qquad rlen_a < rlen_{selected} < rlen_b \tag{4.11}$$

The weighting factor 'W' derived in Equation 4.11 is used to modify the Weibull distribution according to local roughness characteristics. The Weibull distribution shape and scale parameters are set out in Equations 4.12 and 4.13.

$$\beta' = W\beta_a + (1 - W)\beta_b \tag{4.12}$$

$$\alpha' = W\alpha_a + (1 - W)\alpha_b \tag{4.13}$$

Windshear is the change in wind velocity with height above a surface. Close to a surface wind velocity is lower than at higher elevations due to the increased drag associated. A simple relationship is observed where v' is the new windspeed and z the height above the ground.

$$v' = v.\left(\frac{ln(\frac{z}{rlen})}{ln(\frac{z_{meas}}{rlen_{meas}})}\right) \tag{4.14}$$

It is therefore possible to calculate the decrease in wind velocity at any given WTG hub height dependent on roughness.

4.2.3.3 Orography

Orographic elements include such features as hills, valleys and ridges. These influence the wind through speed-up or slow-down effects. For example, the wind decelerates at the foot of a hill and accelerates at its crest. The calculation is set out in [98].

4.2.4 UK Wind Velocity Mapping

The velocity of the air varies according to fixed physical topographic parameters of the area surrounding any site. This data is available in a general form: wind velocities from the The Met Office, topographical data from the Ordinance Survey. Calculated wind-maps for the UK exist that take into account approximations of the above physical factors. Figure 4.6 illustrates the NOABL [151] wind velocity map of the UK which is calculated to a resolution of 1km^2.

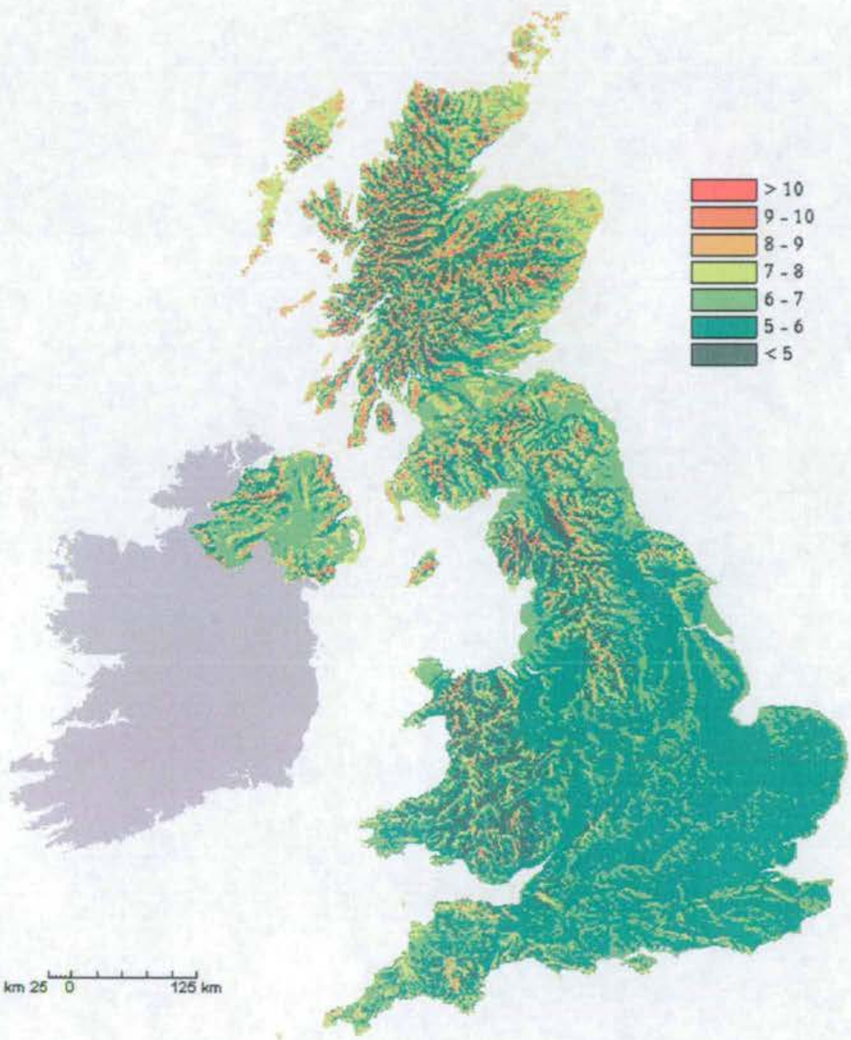

Figure 4.6: UK NOABL wind velocity ms^{-1} map for the UK (25m above ground) [99].

4.2.5 Describing Wind Variation

Wind speed and direction constantly change and are therefore difficult to quantify accurately for power evaluation purposes.

4.2.5.1 Wind Velocity Variance

The relevant time intervals and their effects for the UK may be listed as:

1. Annual.
   Annually there will be some variation in wind due to global climatic effects, the yearly average changing very little in a given locality.
2. Seasonal.
   The passing of weather systems (synoptic variation) usually derived in the Western Atlantic produce a pattern of wind characteristics producing fairly certain patterns.
3. Diurnal.
   Daily wind speed and direction vary depending on time of day. In the UK there tends to be more wind during the day due to the greater temperature gradient between sea and land at that time.
4. Momentary.
   These brief changes in wind speed and direction may be termed turbulent effects. Normally the inertia of the turbine will 'smooth' out these fluctuations although fatigue levels increase.

A Weibull Distribution is the accepted method by which to describe the wind variation over any period (as a probability density function). Equation 4.15 describes the Weibull distribution $Pr(v)$ (where α is the shape parameter, β is the scale parameter) and Figure 4.7 illustrates specific examples.

$$Pr(v) = \left(\frac{\alpha}{\beta}\right)\left(\frac{v}{\beta}\right)^{\alpha-1} exp^{-(\frac{v}{\beta})^{\alpha}} \tag{4.15}$$

It is usual within the wind industry to use a 'shape' parameter (α) of 2 for such a distribution as this best describes the aforementioned variations. This is known as a Rayleigh Distribution [100]. (The shape parameter describes how 'peaked' the distribution is.) Variation in the Weibull distribution is likely depending on specific site characteristics. (See Equations 4.12 and 4.13.)

4.2.5.2 Wind Direction Variance

Wind direction is of importance in determining the layout of WTGs. A WTG should be oriented in such a manner to avoid being in the wind shadow of some obstacle. This ne-

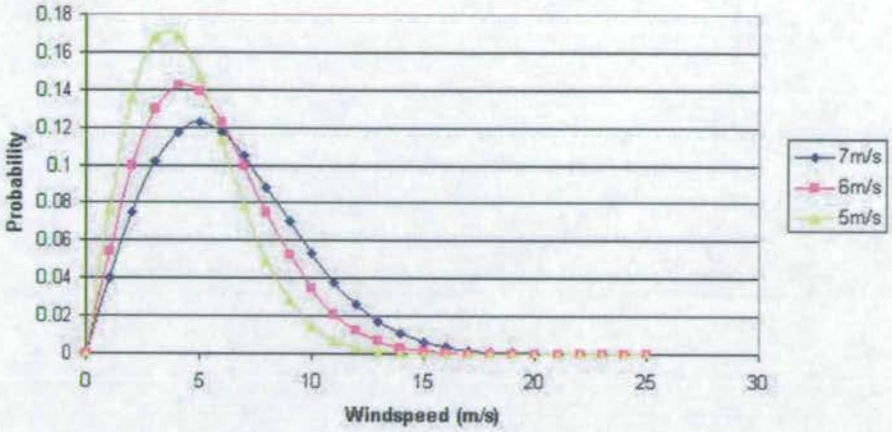

Figure 4.7: Rayleigh distributions for wind velocities of 5,6 and 7ms^{-1}.

cessitates that the direction most free of obstruction be the predominant wind direction. Rapidly varying wind direction, such as that found in mountainous areas, causes local turbulence and increases WTG fatigue.

A wind direction 'rose' records wind direction probability, usually in twelve 30^o sectors from 0 to 360^o. The mean power output from a WTG is calculated for each sector (f_i representing the frequency of occurrence, P_i representing the effects of wind velocity, roughness, shelter, orography) and summed to produce the total power (P_{tot}):

$$P_{tot} = f_1P_1 + f_2P_2...f_{12}P_{12} \tag{4.16}$$

$$P_{tot} = \frac{\sum_{i=1}^{12} f_i.E_i}{\sum_{i=1}^{12} f_i} \tag{4.17}$$

E_i defines the available mean power density (energy flux) for each sector. Variation in wind direction is catered for by the turbine yaw mechanism. This allows the turbine blades consistently to face into the wind independent of wind direction.

4.2.6 Turbine and Generator Characteristics

The turbine power curve (see Figure 4.8) defines the generation characteristics for a specific turbine over a range of wind velocities. The wind velocity at which the turbine begins to generate power is termed the 'cut-in speed' and the wind velocity at which the turbine will no longer generate to avoid damage, the 'cut-out speed'. The turbines in Figure 4.8 have a cut-in speed of $3ms^{-1}$ and a cutout speed of $25ms^{-1}$.

Although the turbine power curve is a continuous function, for analytical purposes it

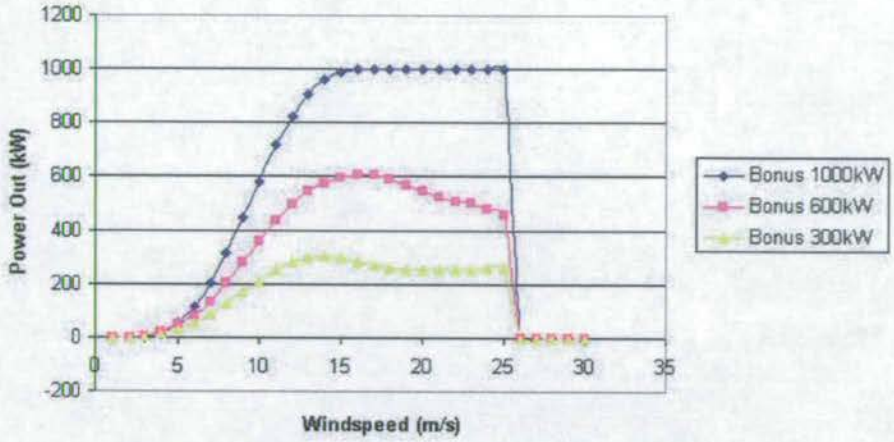

Figure 4.8: Power curves for three Bonus turbines.

may be defined as:

$$P(v) = \frac{P_{i+1} - P_i}{v_{i+1} - v_i}(v - v_i) + P_i \qquad v_i \leq v < v_{i+1} \tag{4.18}$$

4.2.7 Siting

The siting procedure in order to produce the maximum electrical output from a WTG may be listed as:

1. select the appropriate regional wind climatology,
2. determine the influence of roughness and windshear,
3. determine the influence of obstacles,
4. determine the effects of local orography,
5. derive the resulting Weibull distribution at WTG hub height,
6. calculate the WTG power output by use of the Weibull distribution and the specific turbine power curve.

4.2.7.1 Calculating Annual Electrical Power Output

Combining Equations 4.15 and 4.18 and integrating for all possible wind velocities produces the mean total power production (P) from a specified WTG.

$$P = \int_0^\infty Pr(v)P(v)dv \tag{4.19}$$

The analytical solution suitable for numerical solution of Equation 4.19 becomes

$$P = \sum_i \left(\frac{P_{i+1} - P_i}{\frac{v_{i+1}}{\beta} - \frac{v_i}{\beta}} \right) \cdot \left(G_\alpha\left(\frac{V_{i+1}}{\beta}\right) - G_\alpha\left(\frac{V_i}{\beta}\right) \right) \tag{4.20}$$

where $G_k\left(\frac{V}{\beta}\right)$ is $\frac{1}{\alpha}$ times the incomplete gamma function of the two arguments $\frac{1}{\alpha}$ and $\left(\frac{v}{\beta}\right)^{\alpha}$.

The application of Equation 4.20 produces the annual kWh produced by a specific turbine at a specific location. For example, for a 1MW Turbine (Danish, Bonus 1000) with a rotor diameter of 54m and hub height of 45m at a Highland location (Scotland) with a Rayleigh distribution and mean wind velocity of 7ms, assuming standard temperature and pressure (15°C, 101.25kPa), and a roughness length of 0.005m, the annual output can be estimated as follows.

A time interval for evaluating the electrical energy produced over an entire period (for example, an interval of 30 minutes over a period of 1 year) is selected. The Rayleigh PDF (modified according to the local topographical features) returns the likely wind velocity for each interval during the year. The Rayleigh PDF returned wind velocity is used to look up the electrical power output by the WTG from the appropriate power curve (specified in Figure 4.8). The total electrical power produced for every interval during the period is summed to produce the likely total electrical power per year. (2450MWh/annum in this example.) Taking losses and inoperation to be 10% and 2% per annum respectively, produces the yearly electrical output from such a turbine to be 2160MWh.

4.3 Wind Power: The Cost of Development

The costs of implementing a wind power project may be disaggregated to external and traditional costs for each of the stages: site selection, project feasibility, project assessment, construction, operation and decommissioning.

4.3.1 Traditional Costing

Figure 4.9 summarises the typical UK installation costs for a 5MW wind project [104]. Operation and maintenance (O and M) costs amount to between 1.5 and 2% per annum of the original investment [101]. In 1998 the unit WTG cost was £700 per kilowatt of nameplate rated power [102], a 600kW WTG installation therefore initially costing £420,000 of which the turbine accounts for £268,800. Total O and M costs per annum are in the region of £8,400. The cost of decommissioning a WTG site is likely to be returned in full through the sale of the WTG as scrap [103].

The upgrading of the electricity network (and Grid connection) often proves to be the

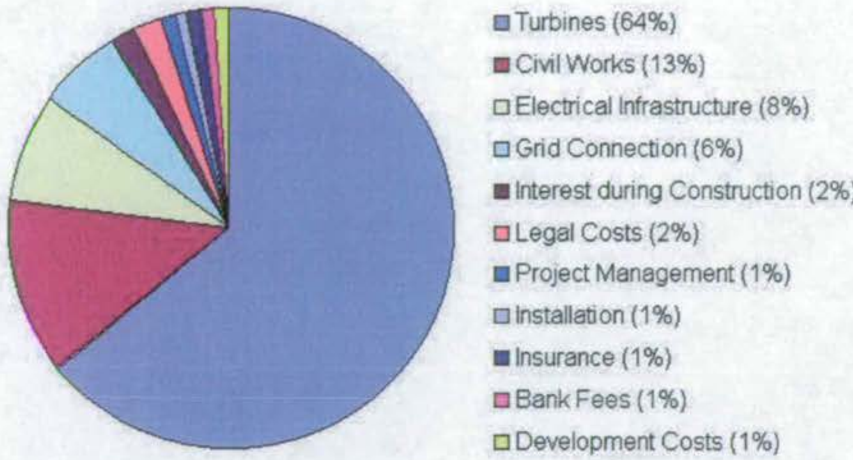

Figure 4.9: The typical capital cost breakdown of a 5MW wind project.

most variable of the traditional project costs. Connection cost is dependent on the distance of new line required to reach the existing network, reinforcement of the existing network to meet system requirements, installation of the necessary protection devices, transformers and switchgear. It must therefore be evaluated specifically for each project, a quote from the local REC (DNO in future) being the normal method.

4.3.2 External Cost and Benefit

Table 4.1 summarises the significant external costs and their ease of quantification [2] listed in order of suspected impact.

It is concluded that the specific traditional costs are well documented and available from manufacturers and their trading associations. The cost of the required capital as applied by financial houses is also well understood and defined. However the usually undocumented external costs and benefits of wind power development are not readily available and require quantification.

4.4 The Inclusion of the Externalities of Wind Power?

Examination of the rationale in including externalities for wind power projects must be justified. Any part of a wind development proposal may be assigned a cost or benefit, the final cost-benefit analysis determining project viability.

[2] D: Difficult, M: Medium difficulty, S: Straightforward

Category	Cost/Benefit	Ease of Quantifyability
Visual	Cost	D
Noise	Cost	D
Ecological	Cost	D
Electromagnetic interference (EMI)	Cost	M
Accidents (public and occupational)	Cost	M
Life cycle analysis	Cost	D
Offset of emissions	Benefit	D
Employment	Benefit	M
Tourism	Benefit	S
Indigenous fuel source	Benefit	D
Support to local communities	Benefit	S

Table 4.1: Significant wind project externalities and quantifiability

4.4.1 Externalities at a National Level in the UK

Based upon the body of evidence contained in recent planning proposals as summarised in Table 4.2 [3] [4], it is clear that externalities (at sites deemed acceptable by traditional cost-benefit methods) are rendering wind projects unattractive. It is equally clear (Table 4.3) that a very large proportion of all wind projects fail to be developed.

Reason for Non-development	Scotland	England	Wales
Visual Amenity	1	2	3
Ecology	1	0	0
Electromagnetic Interference	1	2	0
NFFO or SRO Time Expired [3]	0	10	1
No Council permission [4]	5	13	10
Public Inquiry [4]	0	10	2
No NFFO or SRO contract	0	4	3
Not known	3	11	11

Table 4.2: Rejected Wind Development Planning Proposals (Derived from [105]).

It is likely that previous cost-benefit studies have neglected external cost due to the methodological problems associated with quantification.

[3] In many of the cases where time expired on a NFFO contract, a single operator Ecogen was responsible. It is not known if this developer was hedging it's bets or otherwise. This has been evident in other cases and encourages the belief that wind operators are money oriented and that no place is safe from over-development. A cooperative or united front between developers carefully structuring proposals to avoid development congestion or unnecessary worry to the public would have avoided some of the present PR problems.

[4] Examination of the reasons set out in those applications dismissed by the local council or at a public enquiry suggest that external cost (visual and noise) is the prime motivator, although there is a reluctance to quote this due to its subjective nature.

Status	Scotland	England	Wales
Rejected	11	56	30
Seeking permissions	45	98	46
Under development	5	6	0
Commissioned	4	34	18

Table 4.3: Summary of all UK Wind Development Planning Proposals (Derived from [106] and [107]).

4.4.2 Summary of Local Attitudes in the UK

A number of surveys of public attitudes towards wind power projects have identified major concerns, and are summarised in Table 4.4. These include studies compiled from throughout the UK and for this project. Full detail of the survey technique used for the new study is included in Appendix A.

Specific interest did not centre on whether wind energy was perceived efficient or technically mature, as traditional costing methods are the only true indicator of such qualities, not perceived values. The attitudes examined in the studies are those relating to external cost directly applicable to the respondent. The present study was based entirely on this premise.

Table 4.4 demonstrates the large variation in opinion towards wind power development at a local level. External cost is a concern for a proportion of the public in the form of visual and noise amenity costs, particularly, pre-development (pre- and during construction).

4.4.3 Implications of the External Costs

Section 4.4.1 illustrated the poor success rate in commissioning wind projects. From the results summarised in Table 4.4, it may be argued that externalities do have an effect. Such effects have, in the past, not been considered quantitatively in the assessment of wind energy development. Consequentially there are a number of significant implications for wind energy as a form of RE source.

- A formidable negative public perception to overcome.
- A shortage of 'suitable' sites..
- Diminished investment and returns from wind projects due to failed or time consuming planning processes. (The inclusion of externalities during initial site selection and planning would warn of likely planning application failure, thereby allowing project abandonment before a costly and unsuccessful public enquiry.)
- A lag in the development of UK WTG technology forcing import of technology and skills.

- Abandonment of good onshore sites in favour of the development of higher cost offshore sites.

The cost to the developer in addition to the external cost barriers will be further exacerbated by the New Trading Arrangements as outlined in Section 3.3.3 [5]. The knock-on effect of diminishing wind power development to energy policy is that the envisaged major contribution (Section 3.2.3.1) of wind energy to meeting the UK Government's RE targets is unlikely. Further, a reduced contribution to the legally binding commitments on CO_2 exacerbated by the closure of nuclear stations may result. Thus a likely global external cost (Global Warming) increases for the sake of avoiding a perceived local external cost.

[5] New planning arrangements are likely to be implemented to mitigate some development problems, but their form is currently unclear.

Location	Researcher	Date	Sample	Attitudes of sample as a percentage				
				Spoil Scenery	Noisy	Non-polluting	In Favour	Against
Bryn Titli	Robert Bell Associates	1993	250	-	-	54	80	-
Cemmaes	Market Research Associates	1994	134	8	3	92	86	-
Welsh windfarms [a]	BBC Wales	1994	268	36	-	-	63	37
Kirkby Moor	Robert Bell Associates	1994	254	39	-	45	54	10
Various (4 areas)	Chris Blandford Associates/ University of Wales	1994	457	-	12	90	70	-
Various open days [b]	Research and Auditing Services Ltd.	1994	970	16	16	-	92	8
Coal Clough	Liverpool University (Dissertation)	1996	50	28	6	46	-	-
Novar	Robert Bell Associates	1998	203	12	-	56	68	3
Hagshaw Hill	Author	2000	90	5	1	87	77	9
Scottish windfarms [c]	Scottish Executive Central Research Unit	2000	430	5	1	-	67	11

Table 4.4: Summary of surveys examining the externalities of wind power development [108].

[a] Llandinam, Rhyd-y-Groes, Taff Ely

[b] Kirkby Moor, Haverigg, Delabole, Bryn Titli, Coal Clough, Cold Northcott and Blyth

[c] Hagshaw Hill, Windy Standard, Novar, Beinn Glas

4.5 Defining the External Costs of Wind Power

Recognition and definition of external costs is presently manifested by the requirement of an Environmental Impact Assessment (EIA). An EIA is required for a development of more than 2 turbines or a hub height greater than 15m [109].

For example, in practice the visual impacts are evaluated by a simple visibility analysis. The zone of visual influence (ZVI), or the area of ground from which any wind turbine is visible, is calculated. A map defining the number of turbines visible from each area of ground is calculated and this overlaid on an existing OS 1:25000 colour map of the area in question. The Countryside Commission has attempted to classify aesthetic landscape characteristics and lends advice on developments within each landscape type. This allows possible impacts to be 'quantified' on a broad basis.

Despite the use of such techniques in giving some idea of possible impact (visual and other) they have not been used to optimise windfarm layout or design. Accurate external or welfare costs are outside these types of subjective classification.

Table 4.1 defines the major external costs associated with a wind power development. Each of the categories is now examined as to the composition of functions deriving the external cost.

4.5.1 Visual Amenity Impacts

The foremost external cost is that of visual amenity. Evidence exists that the foremost reason for no council permission or a public enquiry is again that of visual amenity (see Section 4.3). However, people realise that using subjective visual criteria in formal decision making procedures may lack credibility, and therefore rationalise their opposition in terms of features quantifiable in a normal matter [110] such as noise, birdstrikes, unreliability and the relatively small energy contribution per unit as compared to traditional generation methods. To estimate this cost objectively requires quantification of the factors producing the cost impacts.

4.5.1.1 The Range and Extent of Visual Impact

The visibility of a turbine is dependent on the sensitivity of the eye, topographical factors, the atmospheric conditions and the distance from the observer. Although each site will have different characteristics, Table 4.5 summarises the likely maximum visual intrusion at various distances from a windfarm under ideal viewing conditions. Earlier studies such as ExternE have assumed overall WTG heights of 45m [111]. The early Thomas Matrix developed for similar Welsh studies [112] agrees with the ExternE defined impacts, however present developments include WTGs of overall height up to 70m. The Sinclair-Thomas matrix for WTGs of 70m is summarised in the final column of Table

4.5.

Descriptors	ExternE (45m)	Thomas (45m)	Sinclair-Thomas (70m)
Dominant impact due to large scale, movement and proximity.	0-3000	0-2000	0-3000
Major impact due to proximity: may dominate landscape.	0-3000	2000-3000	3000-6000
Clearly visible with moderate impact: potentially intrusive.	3000-6000	3000-4000	6000-10000
Clearly visible with moderate impact: becoming less distinct.	3000-6000	4000-6000	10000-14000
Less distinct: size much reduced but movement still discernible.	6000-12000	6000-10000	14000-18000
Low impact, movement in good light: landscape component.	6000-12000	10000-12000	19000-23000
Becoming indistinct: negligible impact on the wider landscape.	12000-20000	12000-18000	23000-30000
Noticeable in good light but negligible impact.	12000-20000	18000-20000	30000-35000
Negligible or no impact.	20000+	20000+	35000+
Suggested ZVI radius	-	15000	25000

Table 4.5: Visual intrusion with distance (m) and height for WTG developments [113], [114].

4.5.1.2 The Parameters Affecting Visual Impact

The impact of a WTG development on visual amenity is highly subjective and changes due to various factors, the dominant of which may be defined as:

1. Locational physical factors.
   - The existing scenic and landscape quality.
   - The particular landform, e.g. enclosure: confined, enclosed, open or exposed [115].
   - The scale of any surrounding features.
   - The prevailing atmospheric conditions, e.g. cloudy, clear, etc.
2. The form of the proposed development.
   - The number of WTGs.
   - The size of the WTGs.
   - The design and colour of the WTGs.
   - The layout of the WTGs.
   - The rotation and speed of the WTG blades.

The parameters describing the form of the project interact with the locational physical factors to determine the visual cost. Table 4.6 describes current trends in the form of proposed developments in relation to locational factors.

Characteristic	Study 1 [116]	Study 2 [117]	Study 3 [118]	Study 4 [119]
Layout	Scattered preferred	Match to landscape to retain coherence	Match to landscape	Ordered to fit and not overwhelm landscape
Colour	Neutral	-	Neutral or white	Lighter colours (greys etc.)
Number of Turbines	No preference	Slightly dependent on number visible	Dependent on landscape characteristics	Dependent on landscape characteristics
Size of Turbines	-	No significant difference	Depends on landscape scale factors	No suitable conclusion. Transition in scales at 50m
Turbine aesthetics	-	-	Stable, slender, aerodynamic , simple.	Stable, slender, aerodynamic

Table 4.6: Summary of conclusions of visual impact studies.

Table 4.6 is adapted from a number of studies and shows patterns towards certain characteristics, that is: colour, aesthetics and WTG size. It is noted that features such as layout and number of WTGs are often modified to site specific characteristics, perhaps explaining why a scattered layout has been preferred in study 1. Every development site must therefore be considered on an individual basis.

4.5.1.3 Minimising Visual Impact

A number of the controllable 'form of development' factors outlined above may be utilised to minimise visual impact and therefore cost:

The size of the WTGs determines the size of the area from which they are visible (heavily dependent on local topography). Size and dominance are linked, but this is by the existence of objects of known size (such as trees) to be used as scale comparison factors. For example, a large WTG located on flat moorland will be difficult to tell apart from a smaller WTG occupying that same position unless there are supplementary artefacts of known size to provide scale.

The design and colour of the WTG are important. In the UK the colour has often been matched to attempt to blend into the usually grey cloudy sky. To retain a sculptural rather than functional form white may be more effective. The design issues regarding aesthetics are well documented in [120].

The layout of the WTGs is important if the development is to be visually sympathetic to its environment. Certain landscapes will be dominated by specific features and any development should aim to accede to these in order to be perceived as integral. For example, coastline tends to contain strong linear features, therefore a line of turbines may be suitable.

Finally it is noted that lower speeds of blade rotation are less intrusive [121].

4.5.1.4 Population Affected by Visual Impact

Those affected may be described as:

- Local inhabitants.
- Tourists and visitors.
- Local workers.
- Through travellers.

Local residents and visitors constitute the main burden forming external cost. The cost to local workers is extremely small and likely to be internalised through the market for employment. Similarly through-travellers welfare is unlikely to be changed by any measurable amount.

The visual impact pathway taking account of the local population is described in Figure 4.10.

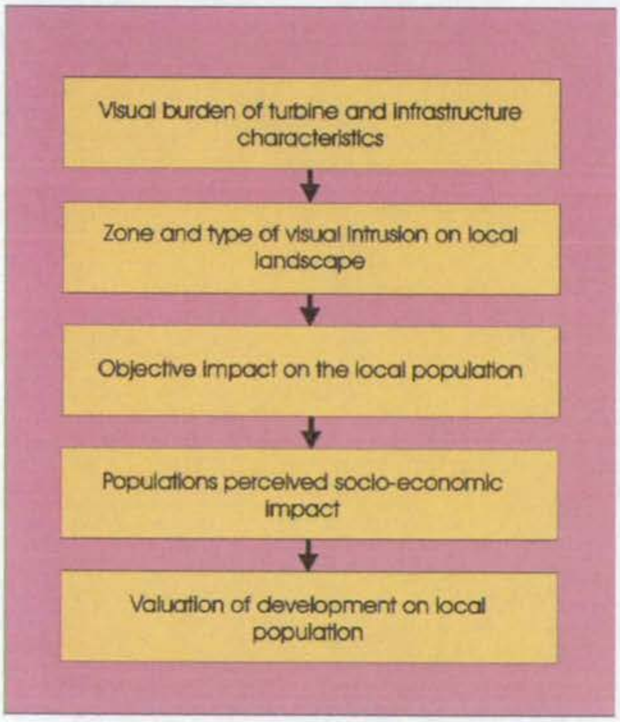

Figure 4.10: The visual impact pathway.

It is therefore possible to define the factors that constitute the functions producing visual impact. That is, the effect of a form of development and the locational characteristics resulting in a visual impact cost to those affected. Such definition establishes the enabling basis for quantification and mitigation of visual cost features.

4.5.2 Acoustic Noise Impacts

Acoustic noise is generated by:

- mechanical noise associated with the gearbox,
- aerodynamic noise associated with blade rotation.

Noise may be minimised through careful design of the mechanical and aerodynamic components. A typical modern WTG produces a sound power level of between 90 and 100 dB(A). At a distance of 350m a number of these turbines normally produce a noise level of 35-45 dB(A) [6]. To place this in context, no UK developers site wind turbines within 350m of the nearest habitation and the noise level of a quiet bedroom is in the order of 35dB(A) [124].

Below the cut-in wind velocity there is no turbine operation and, hence, no associated noise. As the wind velocity increases turbine noise remains constant due to the use of constant speed induction generators. The added noise content from the turbine therefore remains fairly constant over a range of wind velocities.

Recommendations in line with standard assessment practice suggest that the turbine noise level should be kept within 5 dB(A) [122] of the existing night-time background noise level. In contrast many countries have implemented specific numeric criteria for wind noise. For example, Denmark has a statutory order requiring noise levels of < 45dB(A) (L_{Aeq} [7]) for all neighbouring properties and < 40dB(A) ((L_{Aeq}) in noise sensitive locations [123]. British Standard BS 4142 [125] advises that new noise sources should be compared with existing background noise levels and BS5228 [126] advises the application of a 10dB(A) penalty when assessing night-time noise.

The population affected is similar to that for visual amenity but over less distance. The noise impact pathway for a given locality is described in Figure 4.11.

4.5.3 Ecological

The direct ecological impacts of wind energy development on the local ecosystem constituting external cost are:

- impacts on birds,
- loss of wild land,
- impacts of WTG foundation on drainage (e.g. peat bogs),
- increased erosion.

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[6] Detailed calculations are examined in Chapter 5.

[7] The noise level equivalent to the mean sound energy level.

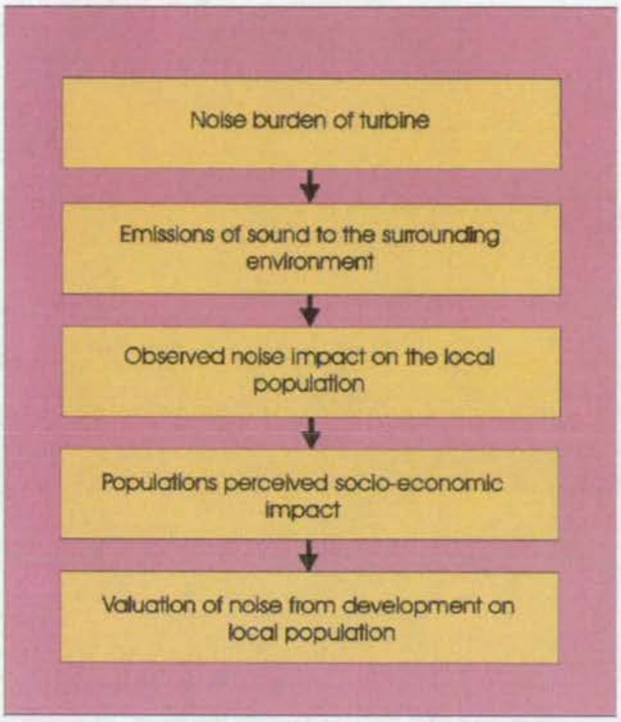

Figure 4.11: The noise impact pathway.

The issue of bird collision with the large, rapidly rotating blades is the prominent concern of the direct ecological impacts. A number of studies from abroad [127], [128] conclude that there is significant mortality, particularly among raptors or if the windfarm is sited on a seasonal migratory path.

Specific UK and North European studies range in suggestion from no measurable impact on local bird populations [129], to the number of birds being killed as being lower than comparable human uses of land, specifically road transport or electricity transmission [130] [8]. It may be concluded that the risk to birds in the UK from wind turbines in areas of normative bird population density is unlikely to be significant. Areas containing protected species should not be considered for development to minimise external cost until further specific research is complete.

The ecological impacts of loss of wild land may be considered negligible as the amount of land lost is equal to the base of the tower (typically 12m^2).

[8]A study was carried out for a new windfarm at Dun Law (Scotland) over a period of 3 months. The areas around the 26 WTGs were checked three times each week, the total number of dead birds observed was 3, of which only 1 was directly attributable to the WTGs. Birds commonly observed at Dun Law include large numbers of Lapwing, Common and Herring Gull, Eurasian Curlew, Common Pheasant, Hooded Crow, Rook, various Wagtails and Tits. All were observed to be aware of the WTGs and frequently fly around them, the smaller birds favouring the transformers at the base of the WTG as a vantage point. A windfarm is likely to be of greatest danger to resident birds at it's introduction due to their relative unfamiliarity with such obstacles, therefore the impacts observed are likely to be a maximum for the resident bird population. Bird carcasses are also most easily spotted in the freshly seeded ground surrounding the WTGs.

4.5.4 Life-cycle Analysis and Emissions

Recent studies have attempted to quantify the energy used throughout a wind turbine's lifetime. The bulk of energy utilised is during manufacture and installation, with recovery of energy from waste possible at decommissioning (Table 4.7).

Stage of Life	Energy Consumption (TJ)
Manufacture	1.900
Installation	0.495
Operation and Maintenance	0.774
Decommissioning	0.522
Scrap Recovery	-0.733
Total	2.958

Table 4.7: Summary of wind turbine (600kW) life-cycle analysis [131].

All associated emissions or their offset are included in a full costing exercise as their contribution to global warming may be significant.

Table 4.8 outlines the associated LCA emissions as g/kWh of WTG lifetime along with those of typical coal plant.

Study	CO_2	SO_2	NOx
	Wind		
ExternE [132]	9.1	0.087	0.036
Norton [133]	6.5 - 9.1	0.02 - 0.09	0.02 - 0.036
	Coal		
UK Government [134]	936 - 1079	14 - 16.4	2.92 - 5.3

Table 4.8: Summary of GHG emissions from wind and coal cycles (g/kWh).

It is assumed that within the UK the baseload plant is nuclear and gas, therefore wind energy substitutes mid-merit coal produced energy. Assuming that WTG capacity factor is 0.3, there are 8760 hours in the year and deriving the average emissions savings from Table 4.8 the emissions offset per annum as compared to conventional plant may be calculated as an external benefit.

CO_2 reduction (tonnes):

$$CO_2 = \frac{(P_{CAP(MW)} \times 0.3 \times 8760 \times 1000)}{1000} \tag{4.21}$$

SO_2 reduction (tonnes):

$$SO_2 = \frac{(P_{CAP(MW)} \times 0.3 \times 8760 \times 15)}{1000} \tag{4.22}$$

NO_x reduction (tonnes):

$$NO_x = \frac{(P_{CAP(MW)} \times 0.3 \times 8760 \times 4)}{1000} \tag{4.23}$$

4.5.5 Accidents

The risks causing accidents or damage to health within the wind energy industry are immediately apparent and relate to:

- The spinning blades.
- Rotating machines.
- Hazards associated with electricity.
- Working at height above the ground.
- Severe weather.

4.5.5.1 Public Accidents

Since the inception of modern WTGs in the early 1970's until the present there have been no injuries due to wind energy production. The wind fuel cycle is *practically risk-free for the public and has practically no potential for severe accidents [135].* In numerical terms the theoretical risk of being hit by a blade fragment thrown from a WTG is comparable to death by lightning (1×10^{-7}) within 210m and considerably less beyond [136]. In most instances a buffer zone or development setback is included in a project for visual and noise mitigation purposes, but additionally serves to distance habitation from possible risk due to even catastrophic failure of the WTG. For example the suggested voluntary UK setback is 120 - 170 m for accidents, and 300m for noise and shadow flicker [137]. No external cost is therefore attributable due to public safety hazards specifically associated with the operation of WTGs.

4.5.5.2 Occupational Accidents

Table 4.9 lists the total accidents within the worldwide wind industry from 1980 to 1994, derived from [138].

Result	Construction Phase	Operating Phase	Dismantling
Deaths	7	5	2
Serious Injury	2	2	0

Table 4.9: Summary of worldwide wind energy occupational hazards.

It should be noted that most of these accidents occurred in the infant U.S. and Danish wind industry without the good working practices adopted within the ESI. For example over half of all the accidents are attributable to two factors, namely no use of a fall-restraint system and non inclusion of a rotor locking pin, both of which are now standard practice. The UK wind industry has suffered no serious occupational accidents to date. This may reflect the lack of wind development, therefore the occurrence of accidents are taken as the current worldwide sector statistics in Table 4.9.

4.5.6 Sources of Electromagnetic Interference

The interference pathways applicable to both the tower and the blades are:

1. Reflection.
2. Scattering.
3. Diffraction.

The periodic motion of the blades causes Doppler shifting of a radio signal. Interference is maximised for highly radio reflective materials such as metal which makes up the blade root. The glass reinforced plastic (GRP) blades are partially transparent. The dominant frequencies for interference are those having wavelengths of the same magnitude or smaller than any component part of the WTG. The following are set aside as the radio communication entities susceptible to such interference [139].

1. Television broadcasting.
2. Microwave links.
3. VOR and ILS for aircraft navigation.

The latter are both to be avoided at the planning stage by consultation with the Radio Communications Agency (RADCOM). Microwave links may be rerouted, while VOR and ILS problems may be avoided by not siting a WTG within a range of 1000m and 5000m respectively of such transmitters [140].

Television broadcasting is therefore concentrated on. Presently television signals contain a vulnerable amplitude modulated video signal although the transition to less susceptible digital broadcasting will diminish such effects.

4.5.7 Local Community Benefits

There are a number of factors concerning wind-farm development that may provide local benefit:

- Employment.
- Tourism.
- Local community funds from the developer [9].

4.6 Quantifying External Cost

The factors and functions defining the impact of each major external cost have been clarified. In order to allow a cost benefit analysis using the common base of monetary value these externalities must be quantified accordingly.

4.6.1 Valuation of Visual Impact

Visual impact is dependent on the local characteristics of landscape, populace attitude and the proposed or existing wind farm. Each site has therefore a very definite and often exclusive set of characteristics. Although hedonic pricing from previous projects may be extrapolated to the project in question as an indirect measure (aggregating all external cost factors), local factors are not taken into account and valuation is error prone.

In order to quantify the visual impact cost it is necessary to describe the development to those affected and elicit their perceived cost. Description is least biased when in the form of a visual representation accurately depicting the proposed development from which those affected may submit their own valuation.

Valuation in the form of opinion is of benefit to a developer in matching the wind project to the locality. However, here it is attempted to elicit a monetary value through the utilisation of Contingent Valuation techniques (Section 2.4.7). The methodology is as follows:

1. Describe the wind development by rendering it visually.
2. Select a representative sample of the affected population.
3. Elicit value responses (CV) from the sample population for visual cost.
4. Regress the elicited values with the attributes of visual quality (see Section 4.5.1.2) (if sample $\neq 100\%$.)
5. Determine the total visual cost by expanding the regression results for all the affected population.

[9] For example, National Wind Power's Windy Standard Wind Farm (Dumfries and Galloway): a fund is managed by the community council totalling £10,000 per annum to assist with local projects and interest free loans have enabled the local community to buy the village shop and post office. [141]

4.6.2 Valuation of Acoustic Noise Impact

Acoustic noise impacts may be calculated for any new noise source against the existing background noise. The dB(A) approach is adopted as it is sensitive to new sources of noise if background noise levels are low, a key point in the likely rural scenario of a wind development. It is also consistent with valuations using hedonic pricing allowing transfer of results.

Factors to be taken into account when calculating noise must include time of day (noise is more noticeable during the night) and intermittency. Tonality may be ignored outwith a distance of 350m [142], a distance smaller than the normal minimum separation to habitation.

Studies valuing the cost of noise impacts have been undertaken specifically concerning aircraft noise affects on populations around airports [143]. Little specific study of the external cost of noise has been undertaken for wind projects and extrapolation of the former studies results to the effects of wind projects is normally used.

The methodology for the valuation of acoustic noise impacts:

1. Determine the existing background noise levels (dB(A)) for the affected population.
2. Determine the noise contribution of the WTGs (dB(A)) for the affected population.
3. Take account of time of day, intermittancy and tonality.
4. Determine the yearly average for the observed sound level change (dB(A)) for the affected population.
5. Value the noise disamenity by dB(A) costing for the affected population.

It is theoretically possible to simulate the noise for any affected individual from the proposed development whereby CV would be possible, but, this was found to have a number of drawbacks. The drawbacks are the inability to: accurately simulate the extremely low levels of noise at distances greater than 500m from a WTG, accurately simulate various weather conditions and accurately represent the dominant tones from a WTG. Further detail is included in Section 6.3.3.

4.6.3 Valuation of EMI

The costs associated with mitigating the EMI affects of a wind power development on communication channels may be calculated as follows:

1. Determine positions and service areas of nearby transmitters.
2. Determine effect of wind energy development EMI on service areas.

3. Propose mitigatory measures (signal relays, amplifiers and active deflectors).

4. Determine the cost of the mitigatory measures.

4.6.4 Valuation of Ecological Impact

UK windfarm development has to date been based on the precautionary principle avoiding any significant ecological cost when considering ecological impact.

Mitigatory or replacement measures have been implemented in a small number of cases where feasible. For example, ecological enhancement programmes creating habitat suitable for eagles and raptors away from the Beinn an Tuirc (Scottish Power) [144] and Beinn Ghlas (National Wind Power) [145] windfarms. The external cost when it exists is equal to the site specific mitigatory measures, zero net ecological damage resulting.

4.6.5 Valuation of LCA and Gaseous Emissions

Although the gaseous emissions derived during manufacture and offset during operation may be quantified with some certainty, there exists great uncertainty towards the quantification of costs associated with energy use and the associated gaseous emissions.

Quantified damage costs of acidification and global warming are normally presented in an aggregated form and are of an uncertain confidence level. Discount rate and period of damage analysis have great effect on cost outcome. Table 4.10 outlines the current range of values for the costs associated with the coal cycle. As the impacts of the wind cycle are negligible compared to the coal cycle, the benefits are taken as the savings from such damage costs.

Study	Discount Rate			
	0%	1%	3%	10%
Cline (1992)	0.0094		0.0014	0.0004
Frankhauser (1993)	0.0066		0.0009	0.0003
Tol (1995)		0.0115		
Hohmeyer and Gartner (1992)	3.1739		0.4859	0.1199

Table 4.10: Possible cost of emissions (p/kWh) [146].

The large uncertainty surrounding the valuation of emission impacts, specifically at transboundary ranges through a lack of a valuation framework, disallows the inclusion of a specific monetary cost at present.

As a contrast to this apparent omission of an external cost, it is noted that if trees were planted to offset the relatively low emission of CO_2 from a CCGT producing 500,000kWh per year, 19,000 'average' trees would be required. A single WTG offsets a similar amount of CO_2 [147]. The emissions saving contribution in the context of global warming occurring may therefore be significant.

4.6.6 Valuation of Accidents

The evaluation of external costs associated with accidents requires a monetary value for a death or injury. An injury cost may be calculated by medical, benefit and non-employment costs. The cost of a death is fundamentally difficult to measure, the most appropriate measure perhaps being the savings from a premature death averted. Table 4.11 [148] describes the current rate of accidents per annum in the UK engineering and construction sectors.

Accident Category	Annual Occurrence	per £10^9 added value
Engineering Sector		
Fatal	24	0.55
Major (hospitalisation > 24hrs)	1,942	44.80
Minor (work absence > 3 days)	13,146	304.00
Construction Sector		
Fatal	137	5.59
Major (hospitalisation > 24hrs)	3,660	149.00
Minor (work absence > 3 days)	17,566	716.00

Table 4.11: Occurrence of accidents in the UK engineering and construction sectors.

Accident Category	Cost per Accident (£)
Fatal	1,625,000
Major (hospitalisation > 24hrs)	49,375
Minor (work absence > 3 days)	750

Table 4.12: Cost of accidents in the UK.

Utilising the specific wind industry accident statistics in Table 4.9, during which period wind turbines delivered 33TWh of electricity and incorporating the costs of UK accidents referred to in Table 4.12, the external cost associated with occupational hazard is deduced to be 6.95×10^{-5}p/kWh.

During 1999 and the first 6 months of 2000, 55 turbines were commissioned in the UK with a total installed capacity of 38.03MW. Thus the average WTG rating is $\approx$ 690kW. Load factor is assumed to be 0.3, lifetime 20 years, and the average capital cost (ex-factory) of a turbine is £700/kW [102]. The occupational accident cost during engineering (manufacturing) is deduced as 3.31×10^{-3} p/kWh using Tables 4.11 and 4.12. Similarly with a knowledge of project construction cost a likely external cost due to accidents during construction may be derived. For example, if construction costs are 40% [148] of capital costs, the cost of accidents during construction amounts to 6.85×10^{-3}p/kWh.

The total cost for occupational accidents derived from the UK construction industry as a whole (0.01p/kWh) therefore overestimates the external cost as compared to that derived from the actual wind energy statistics.

4.6.7 Valuation of Minor Impacts

A number of minor external impacts exist that impact the local community in a beneficial manner. These include employment, tourism, land rental and community funding. The impacts are site and project dependent and must be evaluated on that basis. For example, the novelty of the UK's first windfarm at Delabole in Cornwall attracted 37,000 fee-paying (£1) visitors in the first 9 months of operation [149].

4.7 External Cost Mitigation

Wind energy developments are a local resource based industry. The resource base has been illustrated to be sufficient for development purposes, but the external costs derived from public amenity (affecting planning considerations) have proved to be a constraint on development.

4.7.1 Allocation of Cost

External costs should be reduced to the social optimum and evenly spread throughout involved society for optimal welfare. The specifically local nature of wind energy has often aggregated costs for certain local inhabitants beyond the cost threshold that they find acceptable.

The consistent national, regional and local planning procedures and targets used in Denmark and Germany encourage all of society to take up their part of the cost. Local community ownership offers an investment which pays for the external costs involved. Thus the benefits outweigh the costs at a local level creating public and political acceptance for wind energy.

4.7.2 Public Perception

A large amount of the external cost associated is derived from subjective views of amenity. Better factual education with regard to wind energy can encourage a positive attitude towards amenity thus decreasing the external costs associated. Evidence (see Table 4.4) confirms that public responses are more positive after a wind energy project is operational and the effects on amenity are clear.

4.7.3 Project Design

Each wind energy development may be designed to best fit the locality it is situated in. To this end the British Wind Energy Association has implemented its 'Best Practice Guidelines For Wind Energy Development'. Figure 4.12 illustrates a development chart for the initial stages of development. This model is adopted as the basis for site selection and assessment [150].

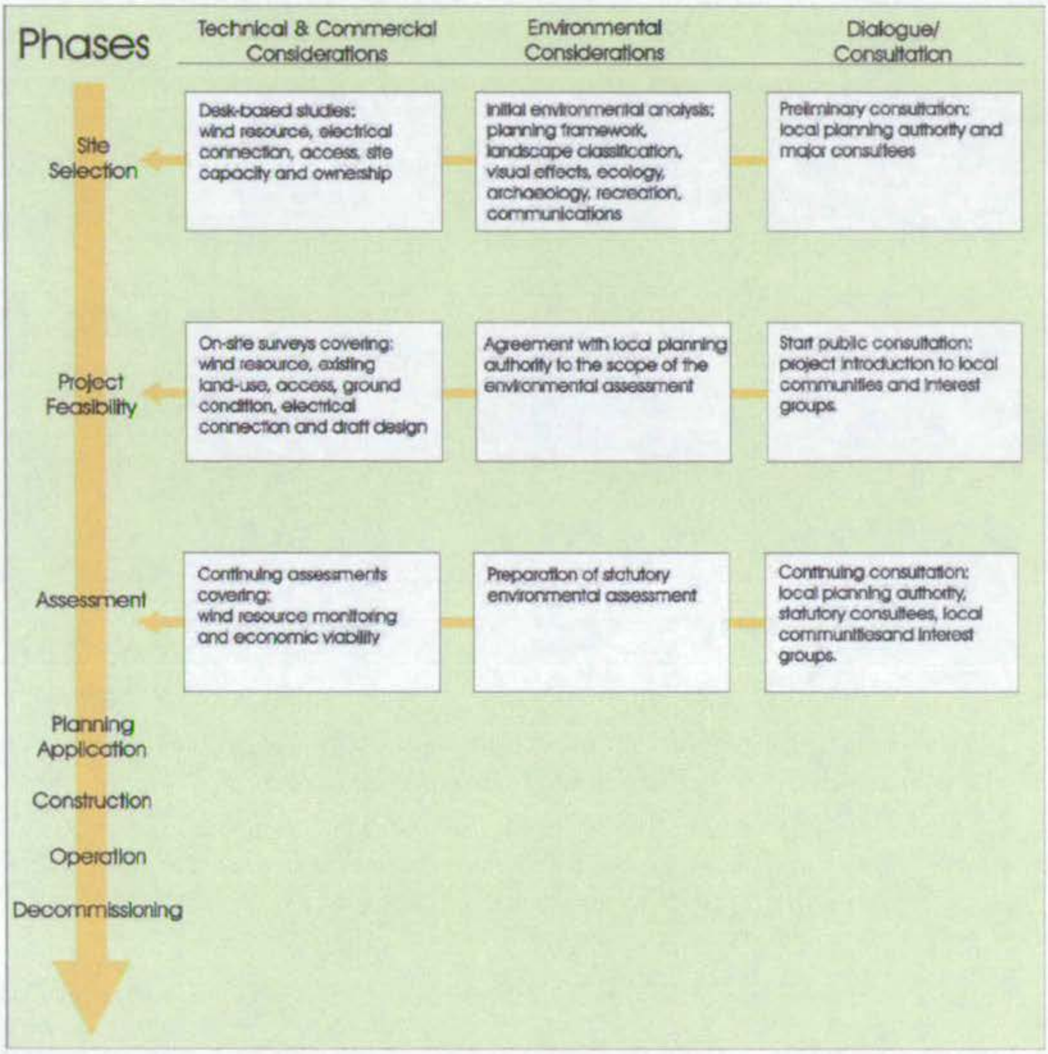

Figure 4.12: The UK 'Best Practice Guidelines' for the design of a wind energy development.

It is clear that in order to optimise welfare (no matter how great the public and political acceptance), the wind energy development must be of optimal design trading off traditional cost and benefit against external cost and benefit.

4.8 Summary

This chapter has introduced UK wind energy development and potential in the context of worldwide governmental, technological and resource terms.

Wind energy penetration has been limited in the UK at a national level by the initially awkward and costly NFFO, SRO and NINFFO processes. The intense competition within these processes drives developers to the best resourced sites, which tend to be those of high amenity value, conflict resulting due to the unquantified external costs.

If government policy regarding renewables and CO_2 commitments is to be met, implementation of wind energy projects may be required. Sound implementation will be by the minimisation of external costs while maximising output, the final cost-benefit analysis determining the usage of wind energy.

The requirements for a successful wind energy project have been described. At present there is no methodology for producing an optimal (welfare) design for a specific wind energy project. It has been determined that all necessary factors may be described, measured (traditional and external) and quantified to a monetary base. Therefore deduction of an optimal solution is possible at any given locality given the required data.

Wind energy projects may be assessed for their overall contribution to national welfare and optimised towards maximum local welfare. The evaluation is therefore highly site and locality specific.

Chapter 5

ExWind: A Wind Power Development Tool

5.1 Software Overview

The requirements for the optimal design and planning of a wind power development have been characterised in Chapter 4. A software toolset is now described to undertake the design and planning of such a development. Geographic location is noted as the basis for this study.

The software toolset developed is known as ExWind (Ex*ternalities of* Wind *Power*).

5.1.1 Objectives and Scope of Implementation

The primary objective of the software is to encapsulate the methodology required to quantify all costs including externalities for any onshore wind project and subsequently return the project's true cost. The scope of the included costs and benefits are detailed in Chapter 4.

The second objective is to optimise trade-offs between external costs and the traditional siting costs of wind energy developments as an aid to the understanding of true least cost planning (LCP). In order to undertake this it is necessary to provide a means of accurately calculating and quantifying the traditional costs and benefits dependent on siting considerations. Thus an application resembling a site design tool has emerged.

At the outset of software development only simple site design tools existed and to date none attempts the quantification, inclusion and optimisation of external costs within a traditional cost-benefit analysis. This is true for all generation options and to the best of the author's knowledge ExWind is the first attempt at producing such a toolset.

5.1.2 Hardware Requirements

ExWind is designed for stand alone 'in the field' use on a portable PC of a widely available specification, (*i.e.*, a Pentium 200MHz processor with 64MB of RAM or better). Subsequent comparisons of processing times refer to this specification and may be extrapolated to other platforms.

The hardware platform has consequence in determining the data resolution (Section 5.4) and process time for computationally expensive functions such as visibility analysis (Section 6.1.2), visualisation (Section 6.1.4) and optimisation (Section 5.6). The PC should be portable to allow on-site surveying and locally produced contingent valuation questionnaires.

5.1.3 Software Structure

Figure 5.1 illustrates the basic top-level structure of ExWind.

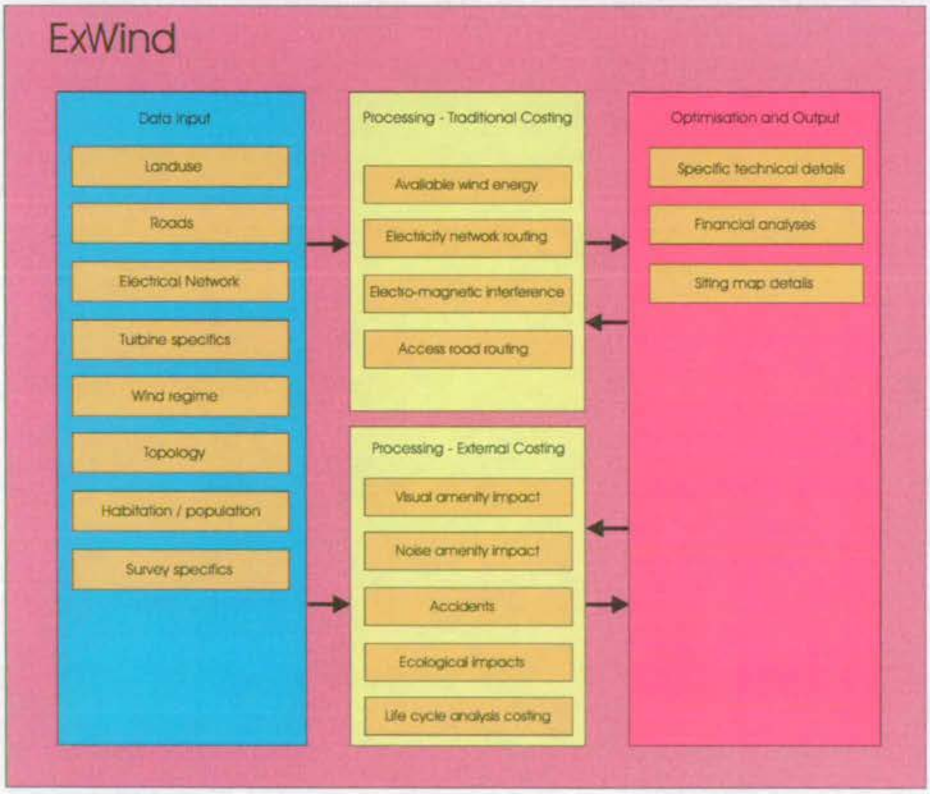

Figure 5.1: Basic structure of ExWind.

5.1.4 Development Platforms

The operating system selected is Microsoft (MS) Windows due to its availability, common usage, provision for high quality graphical display and intuitive operation through graphical user interfaces (GUI's).

Geographic location has been selected as the framework to which all data is referred as the traditional and external design issues are either directly dependent on location or may be accordingly defined. The tool designed to store, manipulate, analyse and display such geographically referenced data is known as a Geographical Information System (GIS).

The GIS platform was chosen according to:

- availability,
- PC and MS Windows compatibility,
- spatial analysis capabilities,
- ease of customisation,
- suitability and availability of the required data format,
- its widespread use within industry and service sectors and
- cost.

Environmental Systems Research Institute's (ESRI's) ArcView GIS was selected as it meets the above requirements to a greater level than competing products such as MapInfo, SmallWorld and ArcInfo. Customisation options exist through the Arc Macro Language (AML). Data is readily available or easily converted to ESRI's 'shape' file format.

Functionality outwith the normal GIS paradigm is required for ExWind, so other functions must be created in a traditional programming language. The criteria for choosing such a development language are:

- performance of the compiled code,
- ease of use of the development environment,
- cost of the development package,
- functionality provided,
- straightforward creation of GUI's and
- ease of interface with ArcView GIS.

Numerous development language options exist to provide the additional functionality unavailable in ArcView. The final choice reflecting the aforementioned criteria is Borland's Delphi 3. Delphi 3 is a rapid application development (RAD) tool compiling Object Pascal and designed to handle powerful database manipulation and integration essential to interface effectively with ArcView GIS.

5.2 Geographic Information Systems (GIS)

A GIS may be defined as:

> *'a computer based tool integrating database operations such as query and analysis with the visualisation and geographic benefits offered by maps'* [152].

The functional building blocks of a GIS are data input, data management and manipulation, data analysis and data output presentation. Figure 5.2 illustrates these functional building blocks , their interaction and role in the planning process as applied to ExWind.

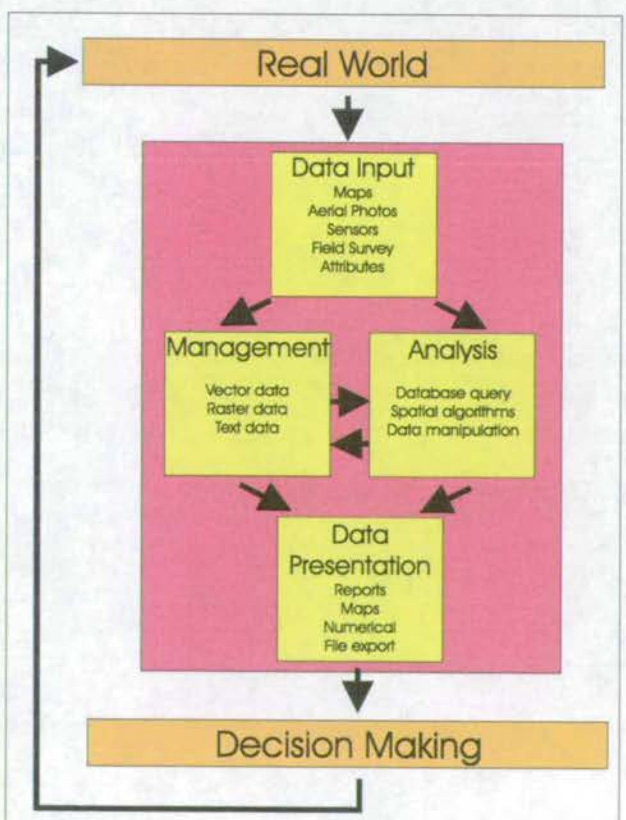

Figure 5.2: GIS in the planning process.

5.2.1 GIS use within the ESI

ExWind may be integrated into compatible GIS systems or make use of their data. The current uses of GIS within the ESI comprise [153]:

- engineering enquiry,
- development and works planning,
- plant replacement,
- network analysis,
- on-line monitoring and control,
- wayleave and easement,
- emergency planning,
- point of sales enquiry and
- marketing analysis.

GIS is in wide usage as facility management within the UK ESI, while public planning bodies commonly use GIS as a means of data storage and geographic analysis. Therefore incorporation of the proposed tool, or the sourcing of relevant data outside the scope of nationally mapped data is possible, providing the REC is willing to cooperate. Datasets exist for all UK nationally mapped attributes from the Ordinance Survey (OS).

5.2.2 GIS Customisation and Application Integration

ArcView GIS has been customised by means of an extension [154] [1] to produce ExWind. The ExWind extension contains the required functionality to evaluate a wind-power project. It is independent from an ArcView project but may be loaded into any project. The ExWind extension contains objects specific to the particular customisation, including the menus, buttons, dialogue boxes, files and functionality required to implement the task required.

Ideally, the GIS would be Component Object Model (COM) compliant for straightforward (exterior) application integration and data transfer yet retain the high spatial functionality of a GIS. Unfortunately such products are only emergent. Therefore ArcView GIS acts as the calling application (or parent) for all external (children) functions, data being passed to and fro between the parent and child via standard database ('.dbf') or

[1] An extension is a type of add-on object database that provides new functionality to ArcView GIS without altering existing projects.

ASCII text ('.asc') files. All child functions appear as seamlessly integrated GIS functions. The GIS waits for control to be passed back from the called child function before continuing with any further processing. Figure 5.3 refers to this hierarchy.

To enhance further the impression of a seamless application, the interface components of the external functions were implemented to be of a similar appearance and layout to the GIS GUI. Thereby overall application uniformity is maintained fostering operator confidence and usability by intuition.

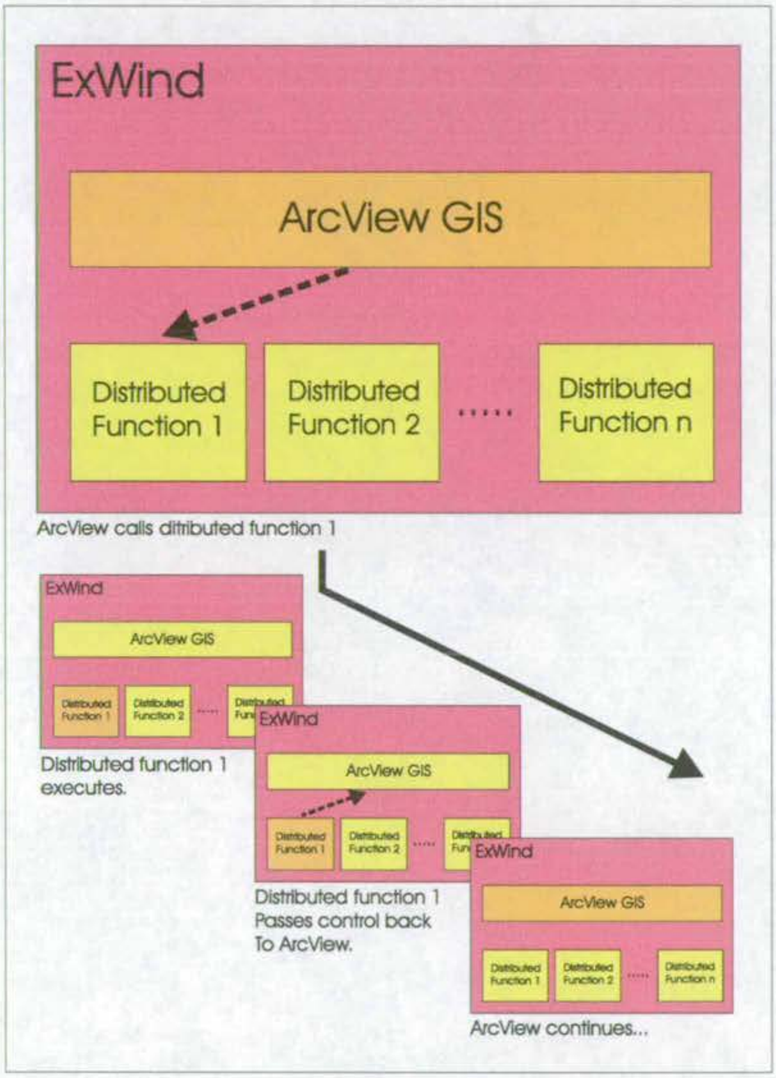

Figure 5.3: Application integration in ExWind.

5.2.3 GIS Operations in ExWind

The inherent ArcView GIS data manipulation properties extend to ExWind, *i.e.* the ability to handle vector data and raster data.

Vector data consists of digitally captured geographic features such as roads, rivers and buildings described by points, lines, or polygons. Vector data is derived from nodes and links. Each vector feature has a unique reference code to which may be added supplementary attributes.

Raster data represents features by a series of pixels or cells derived either by scanning or direct conversion from vector map data. The raster cellsize sets the resolution of the dataset. Correct cellsize selection is critical in maintaining feature accuracy while optimising the storage space required.

Figure 5.4 illustrates the simple use of raster map overlays in spatial analysis. A map of proposed WTG sites is overlaid on a map of areas (cells) visible from a nearby road. A cell by cell analysis is carried out between the two map layers resulting in a raster map determining which areas with a WTG would be visible from the nearby road (red cell).

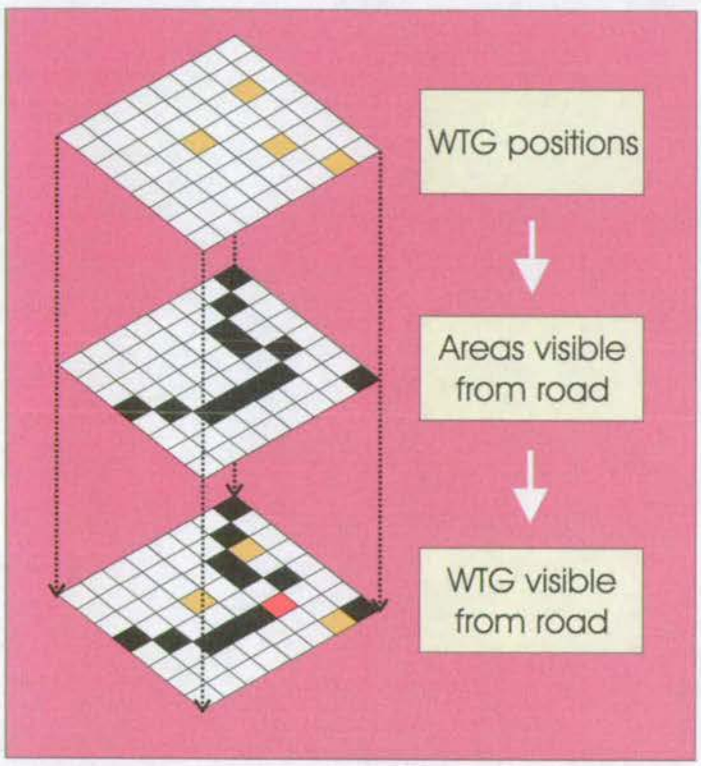

Figure 5.4: Example of GIS raster overlay calculation.

Various complex vector and raster operations are possible to enable the geographic modelling required in ExWind. Further details of general GIS functionality are available in [155] and [156]. The specific manipulation, analysis and output within ExWind are described in later sections.

5.3 ExWind Data Requirements

As noted in Figure 5.1 there are significant data requirements associated with ExWind. Data requirements may be described as those which are geographically referenced and those which describe specific artefact parameters (such as WTG cost, rating, etc.), termed additional data.

5.3.1 The Required Geographical Data

The basic geographical data required by a study evaluating a wind-power project is summarised in Table 5.1. The resolution column denotes the suggested normal scale for vector data and the suggested cell resolution for raster data. The 'converted' column denotes whether the data is converted to a raster format for spatial processing, the figure in parentheses' denoting the subsequent cell resolution.

Map Layer	Source	Data Type	Converted	Resolution
Wind-speed	NOABL	Raster	No	1000m
Landuse	OS Land-line Plus	Vector	Yes(50m)	1:10000
Road	OS Meridian	Vector	Yes(5m)	1:50000
Electric	REC/DNO/User	Vector	Yes(5m)	Variable
Population	MIDAS Surpop (1991)	Raster	No	200m
Elevation	OS Landform DTM	Raster	No	50m
OS map graphic	OS Landranger	TIFF	No	1:50000

Table 5.1: Data requirements for ExWind.

ExWind can utilise any OS digital product, supporting conversion from OS National Transfer Format version 2 (BS7567 [157]) to the ArcView shape (vector) or grid (raster) formats [158]. Vector conversion is performed by ESRI's ntf to arc converter included as an ExWind menu item. OS Digital terrain model (DTM) data may be converted to an ArcView Grid theme, and OS TIFF data may be converted to an ArcView TIF theme (including Tif World File) by specific ExWind conversion applications also available as menu items. Additional map layers may also be derived within ExWind from user supplied data.

5.3.2 Supplementary Geographic Data Operations

Further data manipulation functions have been included as ExWind menu items to aid in the initial manipulation of imported data. These are the ExWind grid theme sample tool which constructs a new grid from a portion of a selected grid theme, and an ExWind menu item facilitating grid theme resizing and translation (required to place accurately non geographically referred data such as the NOABL windspeed data).

5.3.3 Additional Data

The additional data elements (not geographic) required within ExWind may be defined as:

- WTG characteristics.
- Wind direction (wind-rose).
- Economic parameters.
- Electrical connection unit cost.
- Access road unit cost.
- Land and way-leave unit cost.
- Construction and installation costs.
- Operation and maintenance costs.

5.3.3.1 WTG Characteristics

Data defining a specific WTG are entered in the ExWind turbine characteristics database by means of the turbine data form (Figure 5.5). The entered WTG details are stored in a database within ExWind. WTG records may be viewed, added or deleted by the user. WTG details required include: name, rating (kW), rotor diameter (m), cost (£), cut-in and cut-out speeds, available tower heights and cost, manufacturer derived average operation and maintenance costs, average construction costs and installation costs.

Input of the specific WTG power curve is via a series of edit boxes in the manual data entry dialogue, or more efficiently, directly from manufacturer's data by means of the dialog illustrated in Figure 5.6. This provides optical character recognition (OCR) to determine the WTG power curve from graphical input such as a fax.

The requirement to quantify visual impact by visualisation of each WTG (Section 6.1.4) requires specific WTG appearance and form information. The required WTG parameters are: number of blades, tower dimensions, nacelle dimensions, hub dimensions, dimensions of each blade and colour. These details are entered into the virtual turbine creator dialogue box shown in Figure 5.7. A preview option is available to view the subsequent WTG. The compilation of the virtual reality (VR) WTG is described in Section 6.1.5.

5.3.3.2 Wind Direction

Wind direction data may be sourced from the UK Meteorological Office or by local measurement. ExWind provides a dialogue box in which the user may enter the percent-

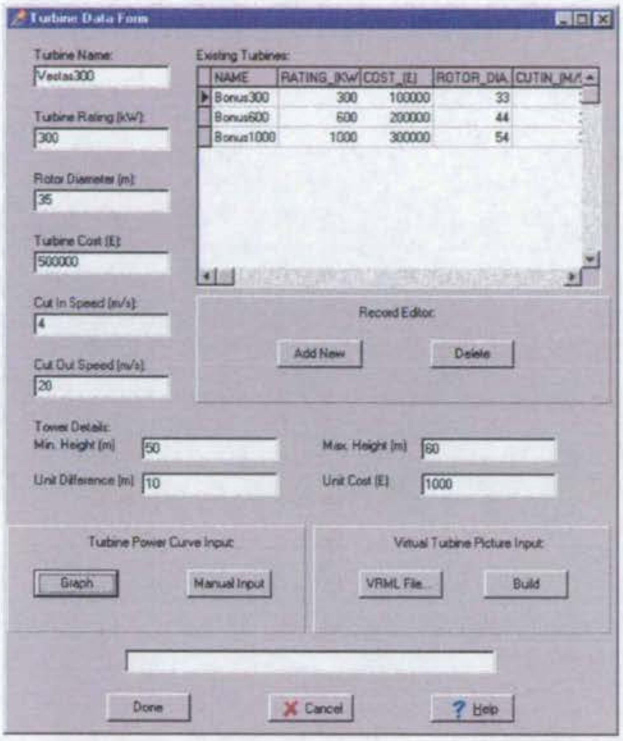

Figure 5.5: ExWind - main turbine detail input dialogue.

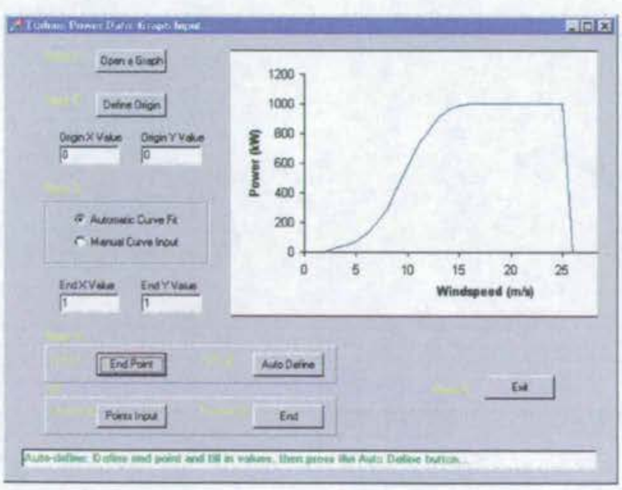

Figure 5.6: Dialogue allowing OCR input of a WTG power curve.

Figure 5.7: Dialogue to define the turbine form and appearance.

age likelihood of wind being in one of the twelve 30° sectors making up the full 360° sweep around a WTG.

5.3.3.3 Economic Parameters

The project economic parameters are those of discount rate, inflation rate, interest rate and electricity purchase price, all user editable to reflect the specific situation.

Specific WTG site costs have been derived from [159] and modified to the present according to the BCIS Tender Price Index for civil works and BCIS Mechanical and Electrical cost index for other elements.

5.3.3.4 Electrical Works Costs

Electrical connection cost is site specific and dependent on the reinforcement required, up to the local point of connection, along with the new transmission line required from the WTGs to the point of connection. The former cost is evaluated by the local network operator while the latter may only be correctly modelled with reference to the local geography.

The overhead lines are rated to the local network operator's fault level at the point of connection. The specific overhead line costs are thus location and project-size dependent. A rough estimation may be derived by determining the over-head line voltage according to the project capacity and taking the cost of overhead line to be £27,400 per kilometre for 33kV lines and £22,840 per kilometre for 11kV lines [160].

On-site electrical engineering work cost varies according to WTG spacing and rating. Table 5.2 illustrates the sensitivity of this cost for a number of possible projects using a radial connection strategy and a WTG spacing of 10 WTG rotor diameters. Cabling is used between WTGs and to the local substation avoiding additional turbulence and visual clutter.

WTG rating (kW)	No. of WTGs	No. of local substations	Cost of local substations (£)	Cost of remote substation (£)	Cabling (£)
330	4	1	51,400	-	49,300
	36	4	374,500	358,500	1,211,500
	63	7	655,500	585,275	2,495,900
750	1	-	16,560	-	-
	14	1	539,000	-	700,270
	27	2	890,760	368,300	1,577,170
1,000	1	-	16,560	-	-
	10	1	436,240	-	486,500
	20	2	730,880	348,300	1,239,700

Table 5.2: WTG site development: on-site electrical costs [161].

5.3.3.5 Access Road Costs

Access road cost is also site specific and dependent on the nearest suitable existing road. A number of options exist where no access is currently available including: temporary roads of steel panels, permanent grass concrete [2], semi-permanent geotextile and crushed rock. The latter is favoured in the UK due to cost and suitability in moorland areas. The associated access costs including hard-standings, passing bays and the turn-off from the public road are detailed in Table 5.3.

Item	Cost (£)
Access road	57,100 km^{-1}
Turn-off	6,852
Passing bay	1,142
Inter-WTG access	46 m^{-1}
Hard-standing	
330kW WTG	2,970
750kW WTG	4,111
1000kW WTG	4,111

Table 5.3: WTG site development: access costs.

[2] A pavement of latticed concrete through which grass may grow.

5.3.3.6 Land Costs

Land cost may be based on local land prices, or often a fixed percentage of the land price paid as rent to the land owner per annum.

5.3.3.7 Construction, Installation, Operation and Maintenance Costs

Installation costs vary according to WTG size, while construction costs are dependent on the required foundation. Foundation costs depend on the local ground bearing capacity and the necessary volume of concrete required to provide the acceptable bearing pressure distribution and adequate stability under the extreme wind load for a particular WTG. This results in the costs described in Table 5.4.

WTG rating (kW)	Unpiled cost(£)	Piled cost(£)
330	18,843	47,964
750	35,973	77,085
1000	58,242	116,484

Table 5.4: WTG site development: foundation costs (Scotland).

Operation and maintenance costs are deduced from previous operating experience of specific WTGs.

5.4 Data Errors

All derived data has associated errors. It is necessary to evaluate the effect of these on the final evaluation produced by ExWind and reduce them where possible. ExWind data is again denoted as geographically related and additional.

5.4.1 Geographical Data

Table 5.5 summarises the errors [3] associated with the geographical data used in ExWind. Three notable sources of error exist in geographical data as applied to a GIS.

[3] Relative accuracy compares the scaled distance between features measured from the map data with distances measured between features on the ground: absolute accuracy compares how closely the coordinates of a point agree with the 'true' National Grid coordinates of the same point on the ground [162].

Map Layer	Source	Scale	Abs. Error	Rel. Error	Revisions (years)
Wind-speed	NOABL	1000m raster	-	-	1992
Landuse	OS Land-line Plus	1:10000	±4.1m	±3.5m over 500m	Cyclic: urban 0.5, rural 5, moorland 10
Road	OS Meridian	1:1250 - 1:250000	±1m	-	Cyclic - major 2001
Electric	User Input	-	-	-	-
Population	MIDAS Surpop [163]	200m raster	10	±12.4	1991 (next 2001)
Elevation	OS Landform DTM	1:50000	±3m	-	1991
OS map graphic	OS Landranger	1:50000	±5m	±10m	Cyclic: 5

Table 5.5: Geographically referenced data errors.

5.4.1.1 Positional Errors Within Vector Data

There are inherent errors in all mapped data, horizontal (defined by triangulation stations) and vertical (defined by benchmarks). These are due to the survey tolerance, change in features over time between revisions, projectional difficulties and human error. All vector data are defined to the accuracy of the underlying map or survey data used.

The required data sources have errors no greater than a 10m absolute error and have been updated within the last six months to nine years. This accuracy in slowly changing rural areas is sufficient for initial estimatory wind project studies (that is, an initial ExWind development study). Higher resolution site survey is necessary at later stages of the development process: such survey data can be manually entered into ExWind. Data entry via GPS can be supported within ExWind.

5.4.1.2 Raster Resolution Errors: Vector to Raster Conversion

If the cell resolution is half that or less of any vector feature, errors will be minimal as stated by the Nyquist criterion. In reality, the resolution must be large to limit data size and thus process time. For example, landuse may be quantified by producing a raster (cell) image of the required area, separating forest from all other uses. Any cell is defined as forest if the majority of its area contains forest. This disregards any small areas of other landuse, inducing error.

Figure 5.8 illustrates a series of pictures captured within ExWind as a raster image. The progressively coarser sampling of the data illustrates the result of losing half the raster cell resolution each time. The data required, and hence processing time, decreases as resolution decreases (by a factor of 4 for a halved resolution), but a certain minimum resolution retaining sufficient representational accuracy is required. (For example, simple experimental data shows that the Prime Minister is recognisable at approximately a quarter of the initial resolution but much less so thereafter.) Therefore careful selection to obtain the maximum cell resolution with realistic processing times is required.

The suggested cell sizes for an ExWind study which may be defined as an approximation of medium accuracy for the initial costing of a wind project are those reported in Table 5.1.

The resolution chosen is defined by the minimum dimension of the artefact or feature in question. For example, 50m by 50m resolution raster data is used for siting data as a WTG occupies this area, or in the case of road network raster data, the minimum resolution is based on road width. ExWind can theoretically cater for much finer resolutions, but unnecessary detail and impractical processing times result.

Figure 5.8: The effect of sampling on GIS raster data.

5.4.1.3 Raster Errors in Matching Overlaid Map Layers

Each raster map layer (refer to Figure 5.4) must be overlaid on top of other layers so that the mapped details match in the horizontal plane. All OS data is defined by the same coordinate system and therefore minimal errors associated with survey occur. Raster data sets such as the NOABL wind-speed map do not adhere to this standard, therefore careful edge and feature matching is required between the layers. ExWind provides tools (Section 5.3.2) to minimise these composite errors.

Randomly sampled points are checked to identify any outstanding errors. The maximum errors occur between the OS vector data and the 1991 Census data. The OS Landline Plus data (relative error of ± 3.5m) is taken as a basis and the census raster information matched to reduce error. Careful census map layer manipulation results in average relative errors between the map layers of ± 12.4m. This error, although significant, is reasonable within the current context of the raster resolution.

5.4.2 Additional Data

The WTG characteristics are derived from manufacturer's data. Error is induced in the manufacturer certified power curve due to the imprecision in calibrating WTG electrical power output against anemometer measured average windspeed under real wind conditions. The effects of turbulence, local wind deflection, and air density contribute to an error of up to $\pm 3\%$ in windspeed translating to an energy yield error of $\pm 9\%$. Certified WTG power curves are therefore taken to have a possible error of $\pm 9\%$

Wind direction is measured at a set of 200 synoptic meteorological stations throughout the UK on an hourly basis. The readings from these stations are extrapolated by ExWind to surrounding areas and modified to account for local topography. Only local measurement by anemometer over a period of at least a year can provide truly accurate wind direction data.

The specific development economic parameters (price of electricity, electrical connection cost, access road cost, land cost, construction cost, installation costs and operation and maintenance costs) are derived or user input as those being currently applicable to such a project at that time and location. Therefore errors are minimal and consistent across all projects evaluated.

ExWind allows user defined error bounds (as a relative percentage error) to be included for each of the above parameters during financial analysis. Three possible financial scenarios are produced: base case, best case, worst case. The full results of each scenario are output to the user (see Section 6.10).

5.5 Overview of ExWind Structure

Figure 5.9 summarises ExWind in operation. In order to evaluate the external cost of a project it is necessary to have a definite project (real or imaginary) on which to base a contingent valuation or further study of the project specific externalities. It is therefore necessary to design a wind power project. Initially this must be based on a traditional cost-benefit basis.

All traditional costs and benefits are calculated as a series of raster cost maps. For example, one such raster cost map may define the cost (£) of a WTG foundation for each map cell while another benefit map might retain the possible output of energy available (as £) for each map cell.

The user may then select their preferred WTG layout manually by mouse interaction (manually accounting for inter-turbine effects and costs), or allow ExWind to find an optimum layout for the required number of WTGs (including inter-turbine effects and costs).

A traditionally costed wind project is output, from which the specific externalities may be derived by the various valuation methods described in Chapter 2. The results (those costs pertaining to the externalities of the traditionally derived project) are then added to the project costs for a full-costing analysis.

The external and traditional cost relationships derived in the new costing may be used to specifically mitigate significant costs (external and traditional) and be further extrapolated to provide external and traditional cost maps for all locally possible WTG positions.

Further WTG layout optimisation is then possible by utilising the newly derived external and traditional cost maps to derive a global least-cost optimisation. A newly optimised layout should prove less costly than previous layouts, the specific externalities again being derived for each successive layout.

5.5.1 Initial Site Suitability Filter

Chapter 3 stated that external costs may be difficult and resource intensive to quantify. It may be deduced from a brief overview of all common fuel-cycles that the majority of externalities associated with a fuel cycle act as disbenefits. Minimisation of the evaluation problem may therefore take place. Those areas unsuitable for wind power development by normal traditional costing methods may be removed leaving the remainder as possible development area options. This reduced area subset may then be further evaluated according to the inclusion of external cost. This greatly increases efficiency by reducing data and thus process time.

Initially a series of filters are provided for use over a large geographical area. Potential WTG sites are identified according to the critical siting parameters of being areas:

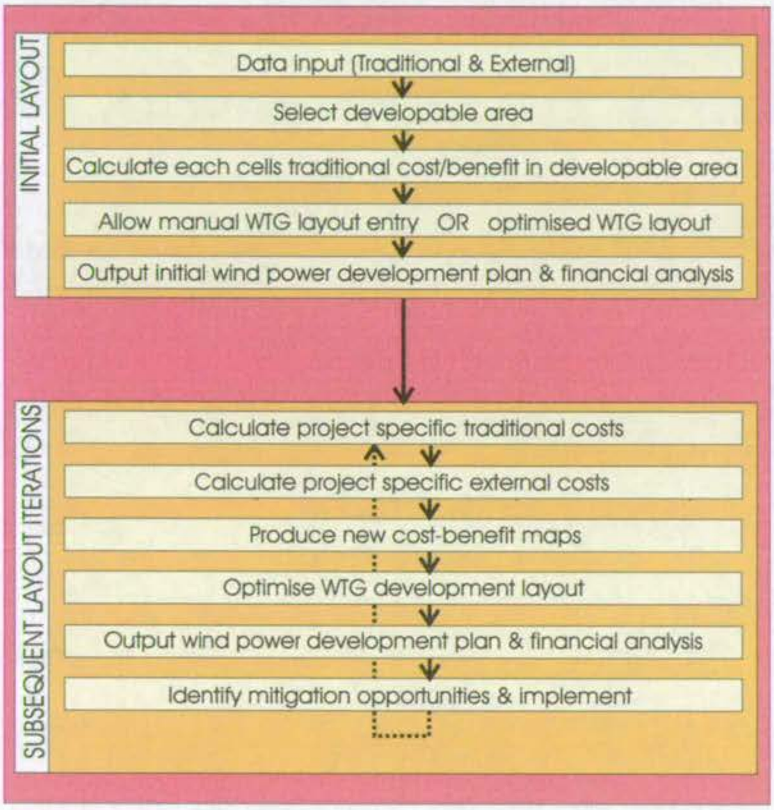

Figure 5.9: Basic functional flow in Exwind.

- of suitable wind speed (i.e. energy output),
- of low population density,
- in proximity to road access,
- in proximity to electrical grid access,
- without forest,
- without water features,
- without a limited development designation,
- of any features as defined by the user.

ExWind provides menu items to create, load and run user defined filters. Figure 5.10 illustrates the filter parameter definition dialogue displayed from the main site filter dialogue. Each of the aforementioned critical siting parameter layers is included.

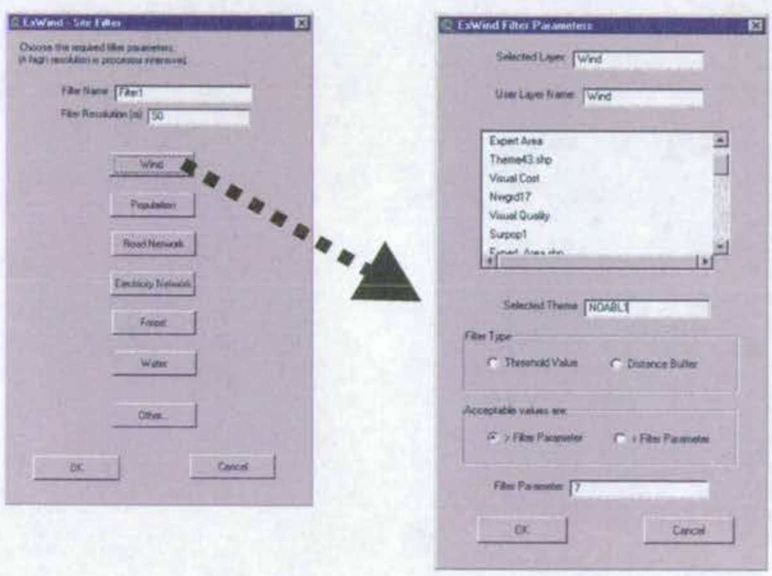

Figure 5.10: Wind filter parameter dialogue activated from the main site filter dialogue.

Filtering is based on comparing the map layer attributes to the required filter parameters and summing the results of all layers. Two methods exist for filtering in ExWind:

- Filter by threshold to the user required maximum and minimum threshold values, (for example, disallow areas with a windspeed of less than $7 \mathrm{ms}^{-1}$).
- Filter by buffer to the user required maximum and minimum distance from a specific attribute (for example, allow areas less than a distance of 500m from roads).

Threshold and buffer values are chosen based on previous experience of producing cost-beneficial projects.

Such coarse filtering significantly reduces the required data, the resulting possible development areas representing the best practical scenarios without external cost. Figure 5.11 depicts such a filter, identifying a limited area (unshaded areas where the underlying map is visible) in which development is possible. Filter 1 (purple) and filter 2 (red) illustrate two separate thresholds set for allowable distance from the road and electricity networks. Both filters disallow the forest and designated areas.

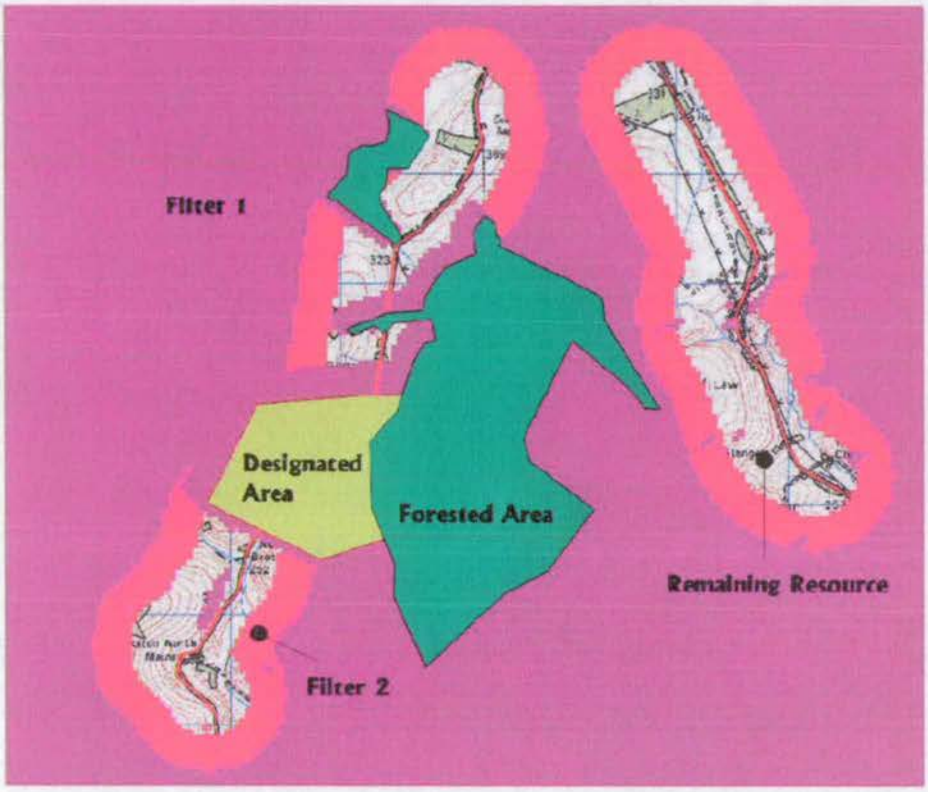

Figure 5.11: GIS output from the coarse filter.

Post filtering, ExWind ranks the possible development areas according to their maximum or summed energy potential, the foremost of which is checked to be capable of containing the proposed development. If the foremost site fails to contain the development, lower ranked areas are submitted until a solution is forthcoming.

The resulting foremost development area may be user selected for further specific site design and cost-benefit analysis including externalities.

5.6 Optimisation and Search Algorithms

Optimisation of each WTG position according to various geographically related costs (traditional and external) while providing maximum electrical output is non-trivial. For example, a position of high electrical output may have a high visual cost, a position close to a grid connection may have a low wind velocity and hence low electrical output. A wind farm contains multiple WTGs sited on land described by such discontinuous cost functions. Further, each WTG may have an effect on subsequent WTGs output by its wake dependent on the prevailing wind direction. Wake effects are limited as inter-WTG distance increases but connection costs increase with the distance between WTGs. To obtain an optimum solution (trading off all cost-benefit factors) to such a siting problem an efficient method for solution is required.

5.6.1 Exhaustive Search Methods

Exhaustive search methods attempt to find all possible solutions to a problem and thereby deduce that which is optimum. For small problems this is possible, although the solution of larger problems becomes inefficient as they demand large resources and time to complete. The number of required calculations grows geometrically with the required number of WTGs. Table 5.6 summarises the time taken to complete various sizes of windfarm siting solutions [4]. The computer used is the 200MHz Pentium with 64MB of RAM described in Section 5.1.2.

Solution Type	Number of WTGs	Completion (secs)	Accuracy %
Exhaustive	4	16	100.0
Exhaustive	8	252	100.0
Exhaustive	16	3941	100.0
Exhaustive	32	65476	100.0(?)
GA	4	2	100.0
GA	8	33	100.0
GA	16	443	99.4
GA	32	8304	99.2

Table 5.6: Solution efficiency of windfarm layout optimisers.

5.6.2 Improved Methods - Genetic Algorithms

Genetic algorithms (GA's) may be used to efficiently solve discrete or continuous problems of a combinative nature containing a large number of variables within a large search space. Such search spaces are too large to be searched exhaustively in an efficient man-

[4] Random layout using 4 possible WTG types, each with 5 possible tower heights, GA accuracy is a percentage error relative to the exhaustive results averaged over 5 GA runs.

ner. GA's are general-purpose search procedures belonging to the family of stochastic search methods, and are based on the mechanisms of natural selection and population genetics [164].

A GA contains a constantly-sized population of individual solutions (chromosomes) each possessing a number of variables (genes) describing it. The genes are the problem variables to be solved, for example, two variables describing the x and y coordinates of each WTG.

The functionality determining how suited the particular individual is to the task at hand is known as a fitness or evaluation function, in this case a function calculating financial return as net present value (NPV) in £. The fitness of each population member may be evaluated against all other members as regards a specific goal, for example, maximisation of NPV for a specific layout.

The initial population may be derived randomly or heuristically and evolves towards successively greater fitness within the possible solution searchspace at each generation by use of genetic operators.

Typical GA functionality may be described as an iterative procedure:

1. Initialise chromosome population.
2. Evaluate the fitness $f(x)$ of each chromosome.
3. Derive new population from genetic operations:
    - Selection - select two parent chromosomes from the population, the probability of selection being proportional to their relative fitness.
    - Crossover - use a crossover probability to determine the resulting offspring.
    - Mutation - use a mutation probability to mutate the offspring at each chromosome locus.
    - Accept - evaluate the newly evolved chromosomes and add to the overall population in place of the worst chromosomes in the last generation.
4. If the solution is good or time is up return the best chromosome, else, go to step 3.

The operators determining the intergenerational changes are selection, crossover and mutation. Figure 5.12 describes these operations pictorially.

Due to the random elements ensured by mutation and crossover a GA is less likely to get stuck at a local optima, and yet is less computationally expensive than an exhaustive algorithm. Further background to GA's is available in [165], [166], [167].

The GAs in ExWind use proportional selection, one or double point crossover and Gaussian mutation with retention of the best generational solution (elitism) based on [168]. The fitness function utilises the specific formulae derived in Chapter 6 and illustrated

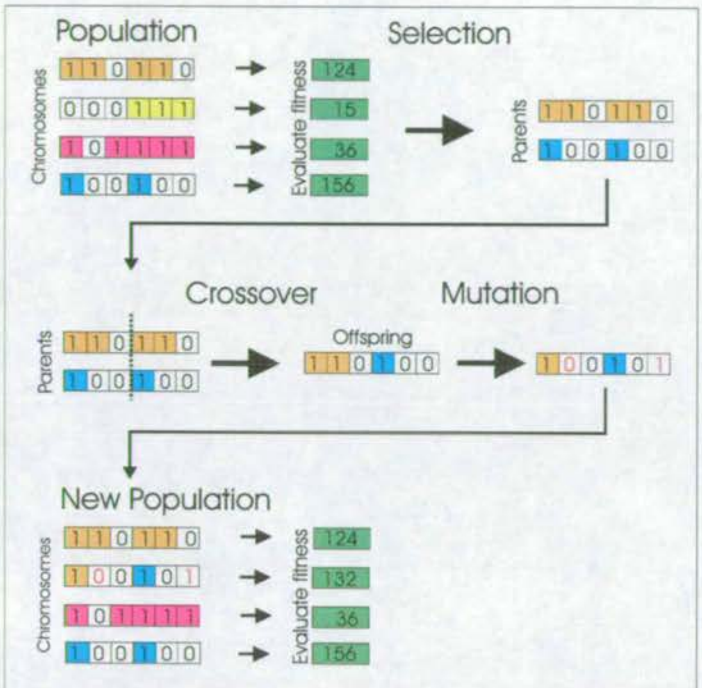

Figure 5.12: Genetic operation within a GA.

in a systems form in Figure 5.13. For clarity Figure 5.12 shows binary integer genetic operators, although the GA in ExWind utilises a Double type representation of values.

The resulting solutions and their process times with the use of such a GA are tabulated in Table 5.6. A highly significant improvement is noted over the exhaustive methods with an acceptable level of error. Efficient solution of large windfarm layouts (100 WTGs) is therefore possible by utilising a GA.

The general limitations of using a GA are that there is a limit to both the number of generational iterations and the population size. That is, estimates based on finite samples inevitably have a sampling error and can lead to non-optimal solution paths.

Specific algorithmic limitations are the suitability of the mutation, selection and crossover functions to a particular problem. This is improved by experimentation with the particular type of problem and these parameters to produce an efficient and accurate solution.

The GA's utilised within ExWind and their results may be viewed by the user, selection of all genetic operator parameters is permitted or ExWind can optimise these parameters to the specific problem based on previous experimental experience.

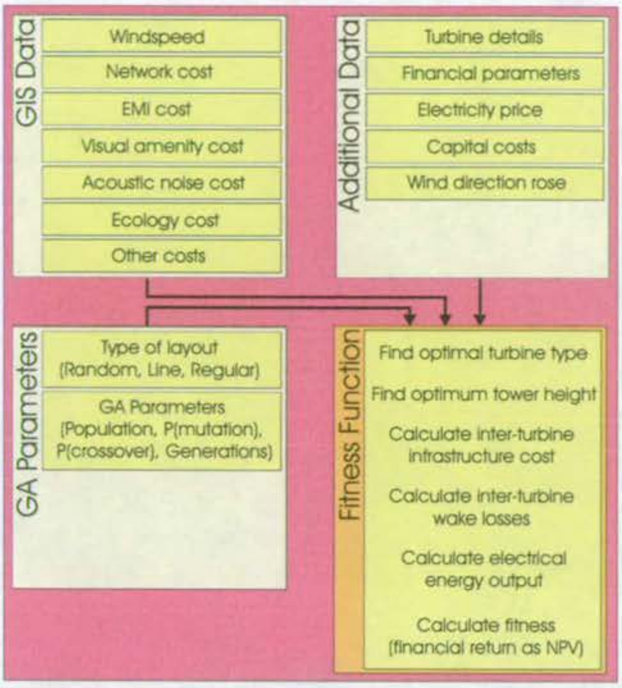

Figure 5.13: ExWind GA fitness function systems structure.

5.7 Summary

A software tool, 'ExWind', has been specified to address the methodological problems described in the true optimal cost-benefit evaluation of a fuel cycle, in this case an on-shore wind development. The required application and hardware development platforms have been described and justified.

The use of geographical information as the basis for such a study has necessitated the use of a GIS. The functionality of ArcView GIS as applied and expanded in ExWind has been described and evaluated. It is concluded that sufficient accurate data is available to complete such cost-benefit studies.

The basic structure and process flow of ExWind has been described. Measures to increase efficiency and decrease process time in the form of an initial coarse site filter and the use of a GA to optimise layout have been discussed.

The specific costing methods determining the traditional and external costs are examined in the next chapter.

Chapter 6

The Functionality of ExWind

Quantification of the parameters defining all relevant benefits and costs (traditional and external) were outlined in Chapter 4, while Chapter 5 provided an overview of the framework and functionality of ExWind. The specific methodology and algorithms required to produce such functionality are now described in detail.

6.1 Visual Amenity

In Chapter 4 it was shown that the costs incurred by the change in visual amenity due to a wind farm are the most significant of the externalities. Quantification is therefore necessary.

Section 4.5.1.2 considered the large variations in landscape and windfarm form which have a direct effect in determining the visual impact. It also pointed out that population density and local attitudes present equally important features in defining the impact. The accurate determination of project visual impact requires a specific study, as general landscape classifications have low reliability in the approximation of impact and no merit in quantification. ExWind uses the methodology described in Section 4.6.1, based on the impact pathway methodology and applies it to a specific wind project. Figure 6.1 describes the basic visual impact costing methodology.

6.1.1 Expert Advice

ExWind contains a small decision support system which recognises 5 major UK landscape types [169], and produces advice to the developer on the suitable layout and size of a development in order to minimise visual impact. ExWind can produce a WTG layout based on manual input, a linear array, a regular grid array or a random layout. The layout form reflects the landscape type identified.

In addition it is recognised that, within the locality of a windfarm, there are areas of

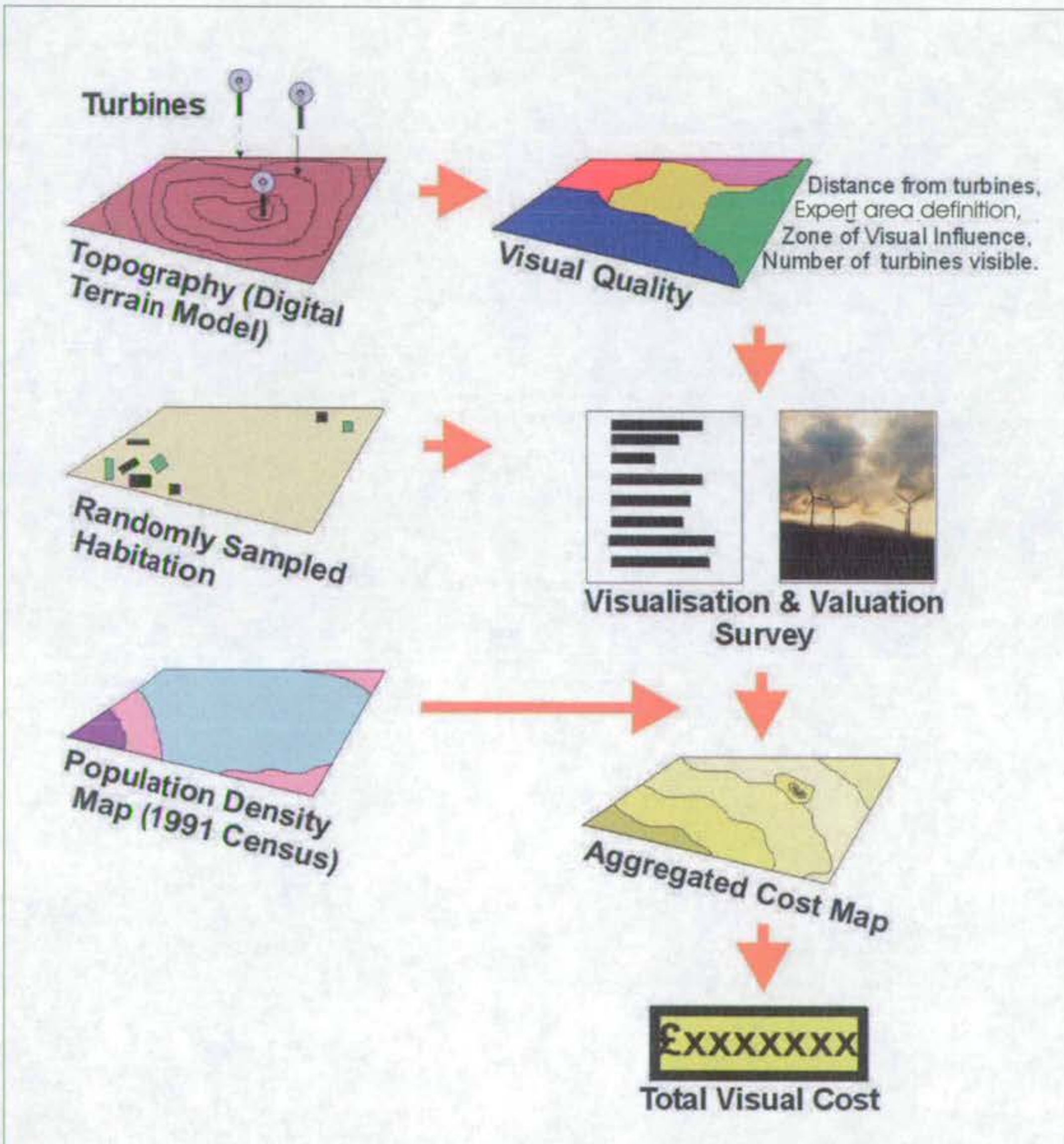

Figure 6.1: ExWind visual impact costing methodology.

differing character and amenity value. ExWind provides an 'expert area' tool allowing the user to break down the locality into its characteristic areas. This enables accurate regression of contingent valuations for visual amenity at a later stage. ExWind does not therefore contain a characteristic set of landscape classifications with which to define areas of differing visual impact. Rather, a possible list of local characteristics (aesthetic, functional, ecological, social) derived from development guidelines [170] and the Battelle Environmental Impact Model [171] is used as the basis for a questionnaire dialogue (Figure 6.2). This allows the user to identify and separate areas containing landscape or amenity values of significant contrast. The expert area tool advises on and undertakes the joining of areas with similar characteristics.

These areas of differing social, landscape and amenity values are later used to develop the visual costings of the region against the visual quality factors without producing an unrepresentative and aggregated average result. This enables specific areas of high external cost to be identified and appropriate mitigation to be suggested. Figure 6.2 illustrates the expert advice and expert area definition dialogues.

6.1.2 Visibility Analysis

A visibility analysis for a raster DTM dataset determines those areas from which the proposed windfarm may be seen. ExWind uses an algorithm that deduces, for each WTG separately, those map points or cells in the surrounding area which are visible. An imaginary line between the uppermost part of a WTG (blade tip in a vertical position) and the cell in question is computed. If no cell along the imaginary line has a higher elevation than the line at that point, then the WTG is visible from the cell in question, as there are no intervening ground features between the WTG and the observer. This is repeated for all valid cells to a distance as required by the user in agreement with Table 4.5.

The process time to complete a visibility analysis is dependent on raster resolution and the size of the area under evaluation. For example, to complete a simple visibility analysis for a single WTG, to a distance of 15km at a cell resolution of 50m requires 42 million calculations [1].

Figure 6.3 illustrates a visibility analysis derived in ExWind for a windfarm (Hagshaws Hill) denoting the number of turbines visible at every map point. This is of limited use in the specific evaluation of external cost, but is the method normally used by wind farm developers in their Environmental Impact Assessment (EIA).

[1] Cells $= \frac{\pi.15000^2}{50^2} = 282743$
Average number of visibility line calculations per cell $= \frac{15000}{2 \times 50} = 150$
Total calculations $= 282743 \times 150 = 42411450 = 42$ million

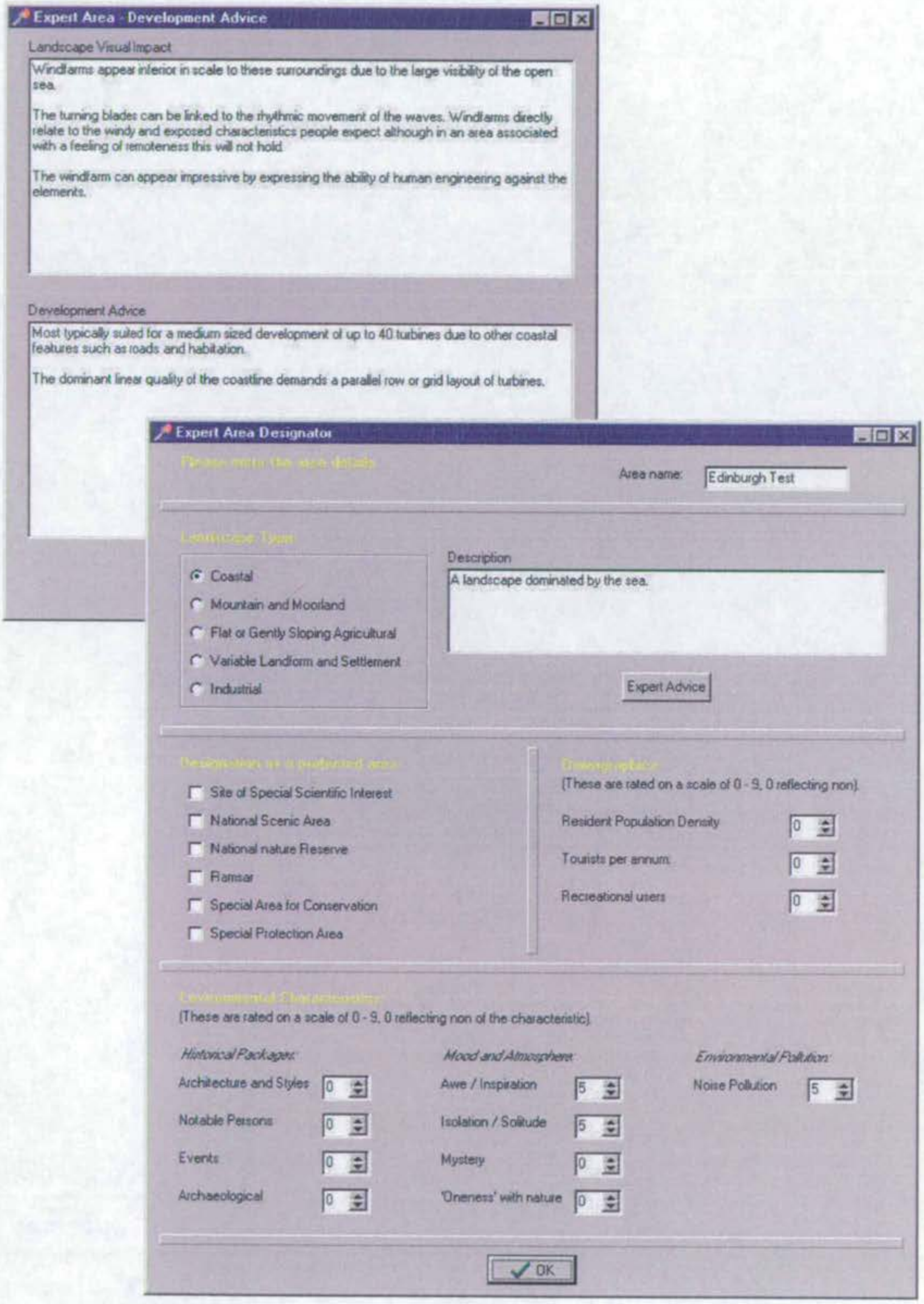

Figure 6.2: ExWind expert advice and area designation dialogues.

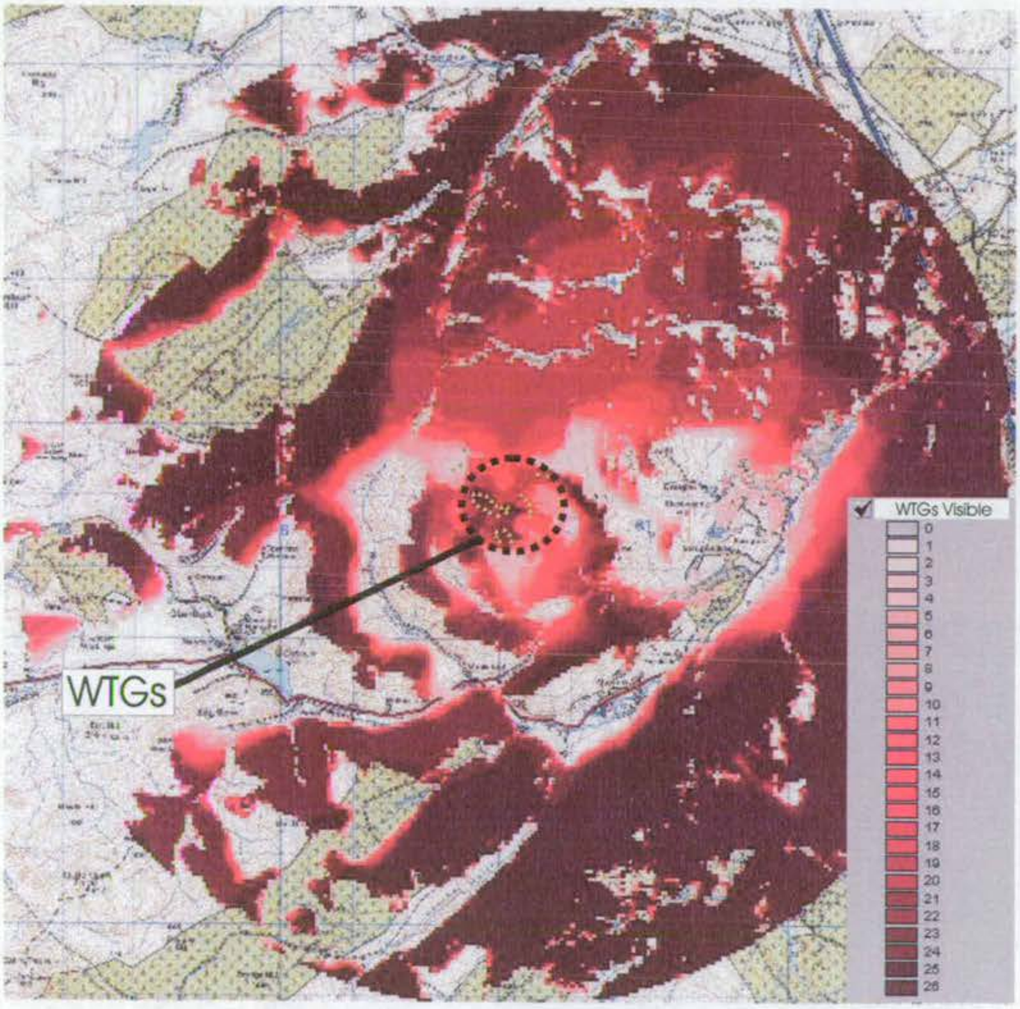

Figure 6.3: Visibility analysis for Hagshaw Hill.

6.1.3 Visual Quality Calculation

Quantification of visual impact in some form is required as a basis for extrapolation of a practically sized sample of CV results to the local population as a whole. There must be visual characteristics to which the monetary valuations relate.

6.1.3.1 General Visual Impact Trends

The spread of valuations within a representative population sample with a similar visual amenity should be of a normal distribution based on slight differences in personal attitude. The physical characteristics of a proposed wind project remaining as the basis underlying the normalised valuations.

The locational factors set out in Section 4.5.1.2 are dealt with by the expert area definer (Section 6.1.1). The physical form of a specific development (size of WTGs, design and colour, rotational speed) is fairly consistent wherever the observer is located and is therefore likely to contribute a consistent valuation within the sample. The layout of the specific windfarm is thought to have some effect on the perceived visual impact although this may be minimised through careful design in accordance with the local landscape as provided by the expert area definer.

6.1.3.2 Specific Local Visual Impact Factors

The dominant parameter affecting visual quality and hence CV is deduced to be distance from the WTG (refer to Table 4.5). This has initially been taken as the basis for defining visual quality.

ExWind can calculate visual quality based on any user defined map layer operations (editable within an AML editor window and automatically compiled into ExWind on registering a script change). The initial studies are, however, based on the premise of impact being directly related to distance from the WTGs: visual quality indices are calculated as a function of WTG visibility, number of WTGs visible, and the inverse square of the distance from the WTGs reflecting WTG dominance with distance.

The fitness of successive layout optimisations within ExWind towards better profitability will endorse or negate use of distance as the central parameter of visual cost.

6.1.4 Type of Visualisation

Section 4.6.1 requires an accurate visualisation of the proposed windfarm in order to elicit realistic visual amenity costings. A number of options for visualisation exist and are outlined in Table 6.1. The need to produce accurately and efficiently a large number

Visualisation Method	Advantages	Disadvantages
Sketches	Cheap, simple	Unrealistic
Models	Adaptable	Expensive, unrealistic
Manual Photomontage	Realistic	Distortion, static
Video	Realistic, motion	Expensive
Automated techniques	Cheap, accurate	Availability
Virtual Reality (VR)	Interactive	Unrealistic, data volume

Table 6.1: Comparison of methods for visualisation.

of high quality visualisations as required by a CV survey rules out the first four visualisation methods, namely sketches, models, manually derived photomontage and video.

Forms of the later two visualisation methods were produced for a well known local scene (Arthurs Seat, Edinburgh) and evaluated by a sample group of 63 people. The three visualisation methods used were:

1. 3D virtual reality derived from ArcView GIS 3D Analyst [2], Figure 6.4.

2. 3D virtual reality derived from ExWind VR generator (Virtual Reality Markup Language (VRML) world), Figure 6.5.

3. 2D photorealistic montage derived from VR WTG and locality photograph by ExWind Figure 6.6.

Questions evaluating user responses to each type of visualisation were asked. Responses were taken as marks out of ten, higher marks denoting greater approval. The results are summarised in Table 6.2 below. It is evident from Table 6.2 that with the limited resources available to a potential developer the photorealistic montage is of greatest benefit, but the ExWind VR generator is also perceived to have benefit in producing an overall impression of a wind project and is therefore retained within ExWind.

Characteristic	GIS Produced VR	ExWind VR	VR Photomontage
		Average marks out of 10	
Time to render	5	3	7
Likeness to reality	1	2	8
Scene recognisability	1	3	9
Overall project impression	1	5	7
		Percentage	
Preferred technique	0	13	87

Table 6.2: Responses to visualisation techniques.

[2] An ESRI ArcView extension producing 3D models from GIS data.

Figure 6.4: GIS produced virtual reality.

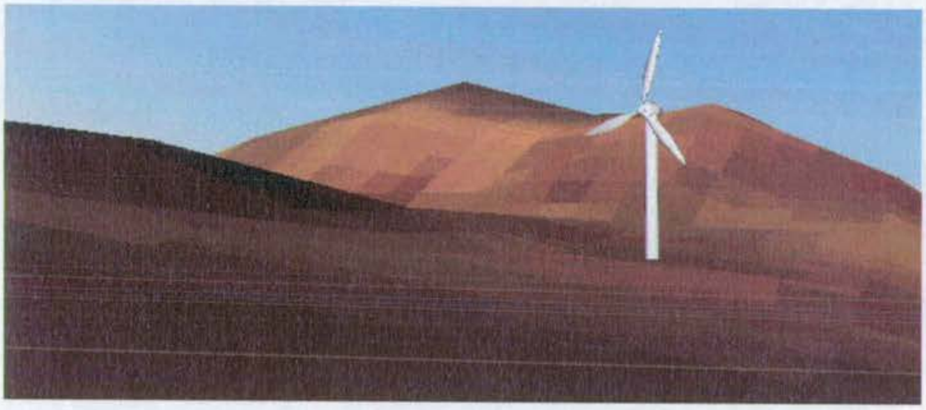

Figure 6.5: ExWind produced virtual reality.

Figure 6.6: ExWind photorealistic montage (VR photomontage).

6.1.5 Creating the Visualisation

Figure 6.7 summarises the creation of an ExWind visualisation. Initially ExWind exports

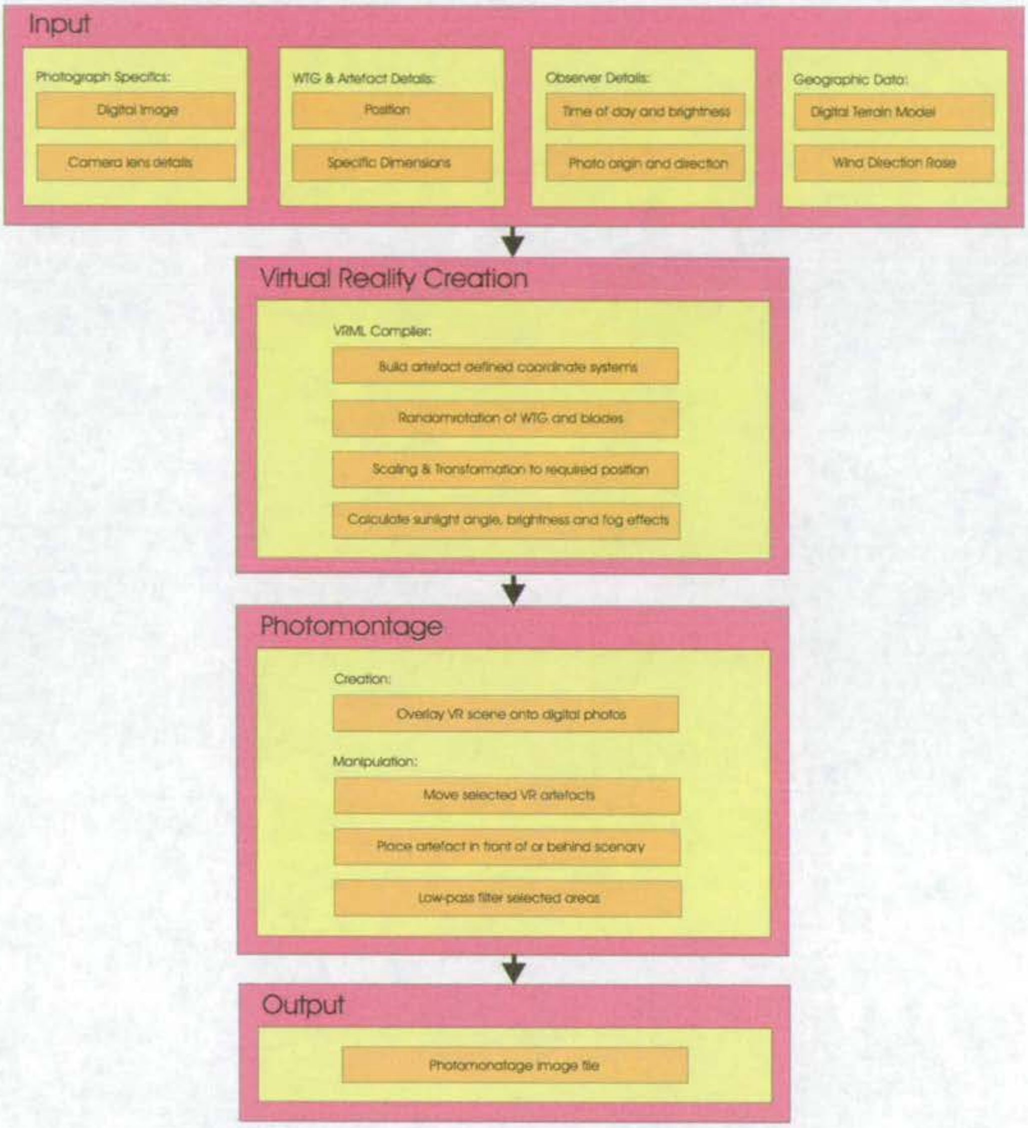

Figure 6.7: Methodology behind an ExWind visualisation.

the required GIS DTM, WTG, artefact and observer positional data to an additional Delphi produced application called 'Virtual Creator'. Virtual creator derives a Virtual Reality Markup Language (VRML) [172] 'World' file containing the form of all visual components from the project specific data passed by ExWind.

The WTG form is specific to the type of WTG as entered in the turbine characteristics definer (Figure 5.7). Further VRML artefacts of any type defined by the user may be called up by the virtual creator (for example, transformers, substations, poles, overhead lines, mitigatory measures) and included in the world file.

Additional reality is added to the VR WTG rendering by inclusion of a random WTG axial blade rotation and by facing the WTG in the dominant wind direction with a small random nacelle rotation. Fog or mist may be added to reflect local conditions; thickness can vary either linearly or exponentially with distance [173] and the range of visibility is user editable.

A photograph is taken of the area containing the proposed wind development at the observer position using a digital camera. The VR world created 'looks' from the observer position in the direction the picture was taken. The VR world is later displayed with the same lens characteristics as those of the camera used.

The lighting in the VR rendering is matched to that in the photograph by use of the sun angle equations described in the section on shadow flicker (Section 6.2). The sun's specific local altitude and azimuth angles are calculated to provide the lighting vector for the VR world. The exact vector is calculated by knowledge of the position of the observer, the time of day the photograph was taken and the brightness of the day. These details are entered along with the photograph details for each observer by means of the 'Observer Details' dialogue shown in Figure 6.8

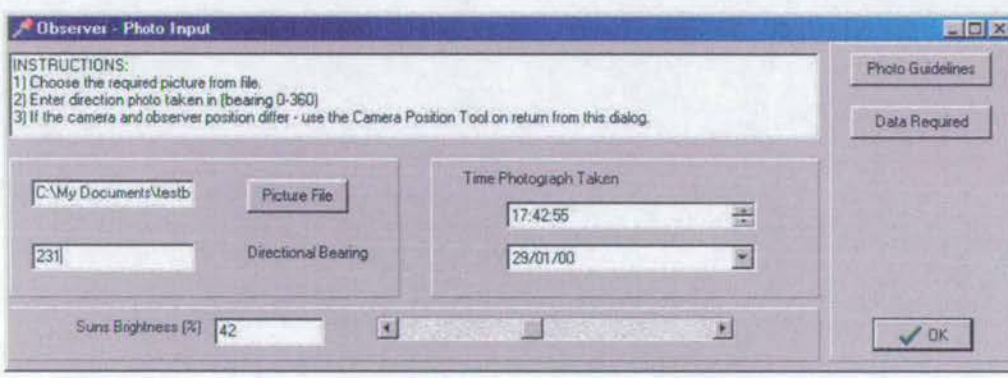

Figure 6.8: The observer details dialogue.

Once accurate VR rendering of the proposed wind project form is complete, it may be viewed as an interactive VR scene (Figure 6.5) within an Internet browser (with VRML plug-in such as CosmoPlayer) or merged with the relevant photograph to produce a realistic graphic (Figure 6.6).

The advantages of this computer aided VR and photomontage technique over current visualisation methods are:

- provision of project visualisation from any specific location,
- high quality output including local atmospheric conditions,
- quality output at any distance from an object (0 to infinity),

- ability to visualise other relevant project artefacts including mitigatory measures,
- ability to render specific scenes at site quickly and efficiently.

6.1.6 Graphics Editor

ExWind includes a post-visualisation graphic editor to allow user interaction with the VR produced photomontage. The tools included further enhance the quality of visualisation. The lower portion of Figure 6.7, referring to photomontage operations, summarises the image manipulations performable.

All VR rendered artefacts (WTGs and other) may be moved within the photomontage relative to the original photograph. This allows recovery from GIS data errors. For example, when using a raster DTM of 50m resolution, the elevation over that 50m is averaged. If the WTG is situated on a small dip within such a cell, it is likely that it will have been placed a little too high in the VR rendering as compared to the real life feature in the original photograph. In an extreme case the WTG may appear to float above the ground. This may be corrected either by a lower DTM resolution or graphically by the user.

Not all artefacts making up a scene are detailed in the geographical data. For example, trees, or even their leaves. Their appearance in the original photograph may mask a WTG. Therefore a graphical tool has been produced to allow the VR rendered artefacts to be set behind or brought in front of any photographed feature.

Finally, to create a measure of visual join between the VR rendering and the photograph a low-pass filter tool is available. The user may select such areas as the interface between the WTG tower and the ground and merge these by use of low-pass filter techniques.

The completed graphic is saved and stored in the observer database within the specific observer record to which it belongs. The picture file is automatically accessed during the CV survey for that particular observer.

6.1.7 Population Sampling

The whole local population affected by the proposed wind development should return their cost valuations of visual impact. The logistics involved in determining every individual's CV may be large, therefore a sample of this population is used to evaluate visual impact by CV and this carefully extrapolated to the whole population.

Population data is derived from local habitation maps or the 1991 Census population map surface. These are randomly sampled to the desired percentage and in the case of population surface maps, habitations selected by nearest-neighbour analysis. Thus a representative sample of the local population is obtained without the bias present in telephone or supermarket surveys which arguably only sample a specific cross-section of the population.

The sample population is then visited at home and spends some time undertaking the CV survey for the specific wind project in question. The specific visualisation is created at each individual's home using the digital camera and visualisation techniques described.

6.1.8 A Contingent Valuation Survey

A CV survey could encourage a biased view of a project through disinformation and thus increase or decrease any external costings. For example, by stressing the clean electricity resource provided by wind while making no mention of visual amenity impacts, a lower costing may result. It is of the utmost importance not to underestimate such costs by providing impartial information to provide true costings. Such marketing tactics play no role in determining a projects' true worth from a public viewpoint, even though the private party (developer) may benefit. It is recommended that if such valuation is to retain credibility and be broadly acceptable as an evaluation, parties other than the developer (e.g. the local authority and local or national public interest groups) must be consulted.

ExWind administers a computer based CV questionnaire to each member of the sample population. The questionnaire is tailored to include the locally relevant photomontages and detail applicable to the member of the sample population providing the CV. The structure of the questionnaire may be broken down as containing :

1. A balanced introduction and scene setting.
2. An accurate description of the proposed wind project.
3. An identification of interviewee's status,
    - socio-economic,
    - extent of specific knowledge,
    - concern and expenditure on feature to be valued,
    - personal preference on related issues.
4. A basis for WTP or WTA valuation (e.g. electricity bill).
5. A valuation of WTP or WTA.
6. A reason for the valuation.

ExWind allows the tailoring of CV study questionnaires via the CV Questionnaire Editor menu option illustrated in Figure 6.9.

Various questionnaires may be designed and used to match specific scenarios and circumstances. The questions used to elicit the final costings should be published with the final costings to retain study transparency. A sample CV questionnaire is presented in Appendix A.

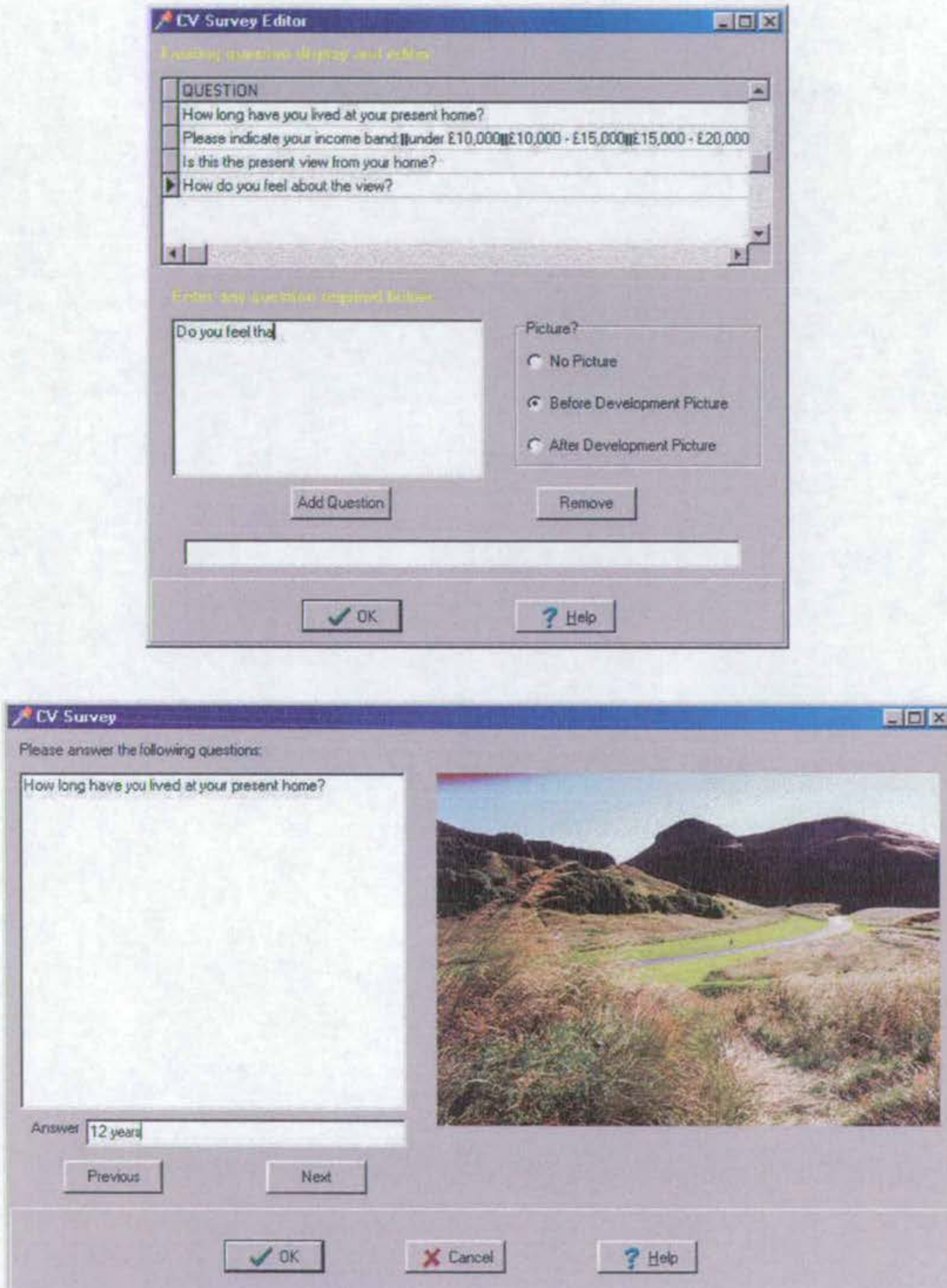

Figure 6.9: The CV survey: editor and questionnaire dialogues.

6.1.9 Determining the Visual Amenity - Cost Relationships

The personal CV valuations from the sample population may be viewed and processed within ExWind's survey data processing dialogue (Figure 6.10). This allows for the extraction of the necessary CV questionnaire data and the removal of 'protest bids' (Section 2.5.7.1) if required. The data processing dialogue operates in a similar manner to a Microsoft Excel Worksheet.

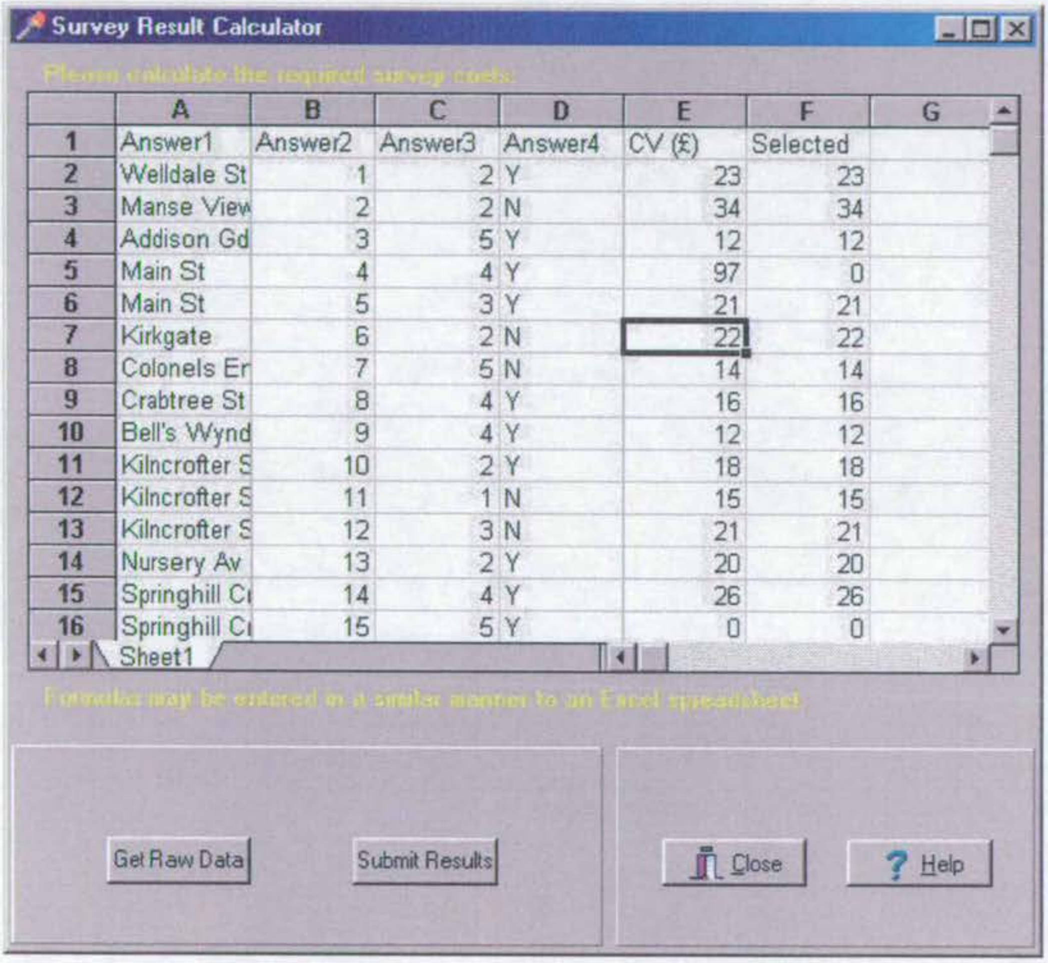

Figure 6.10: The CV survey: data processing dialogue.

The processed individual monetary visual impact values belonging to each member of the sample population are returned to the associated records in the observer's database. These personal valuations are then regressed against the visual quality index derived at each individual's home, producing a formula associating monetary values with visual quality for each specific area (Section 6.1.1).

These derived formulae are used to extrapolate the visual impact costs from the visual quality map for all the affected population. The total visual impact cost of a wind development is returned as a cost map.

6.1.10 Visual Cost for Large Areas

Once the visual quality factors determining visual impact costs are known it is possible to evaluate all possible WTG sites in that locality, the initial assumptions deriving the costs remaining true.

Figure 6.11 illustrates cost maps based simply on the number of local inhabitants for whom the WTG would be visible. The cost maps relate to a WTG hub-height series (10m intervals between 20m and 60m) at Dun Law (UK grid reference 346000, 657600). Each map point is taken as a $50m^2$ cell. The resultant map series shows the visual impact of placing a WTG of a set height in each cell. The study covers an area of $1km^2$ in which WTG location is possible and assumes the range of distinct visual impact is 7000m (Section 4.5.1.1).

Such map series may be used by the GA optimisation technique to optimise visual impact costs with all other costs. For example, increased WTG hub-height increases the possible wind energy capture but raises the cost of visual impact. The visual impact cost as a monetary value may thus be directly traded against the monetary benefits of the electricity produced for all possible WTG positions and the best sites selected.

Such analyses are extremely computer intensive. The above study took 35 hours on a Cyrix 166, 18 hours on a Pentium 200 and 12 hours on a Pentium 266, all with 64MB of RAM. However, the cost of computing is likely to be outweighed by the envisaged savings from such a study.

Conceptually it is possible to create a national map of visual impact. Visual impact is applicable to humans and their presence is thus the basis. The number of humans visually affected by any particular artefact may be derived from:

- the height of the artefact above the ground (ZVI),
- the maximum distance to which the artefact can be clearly seen,
- the relationship of visual impact with distance,
- the population at the point in question.

The benefits of such a study are that visual amenity at any location dependent on an artefact (not necessarily a WTG) of a certain height may be looked up during the planning phase and evaluated against all other planning constraints. Regular updates in synchronisation with new census figures would be necessary.

To scale up such a study to national levels presents an enormous computational undertaking (refer to Appendix B).

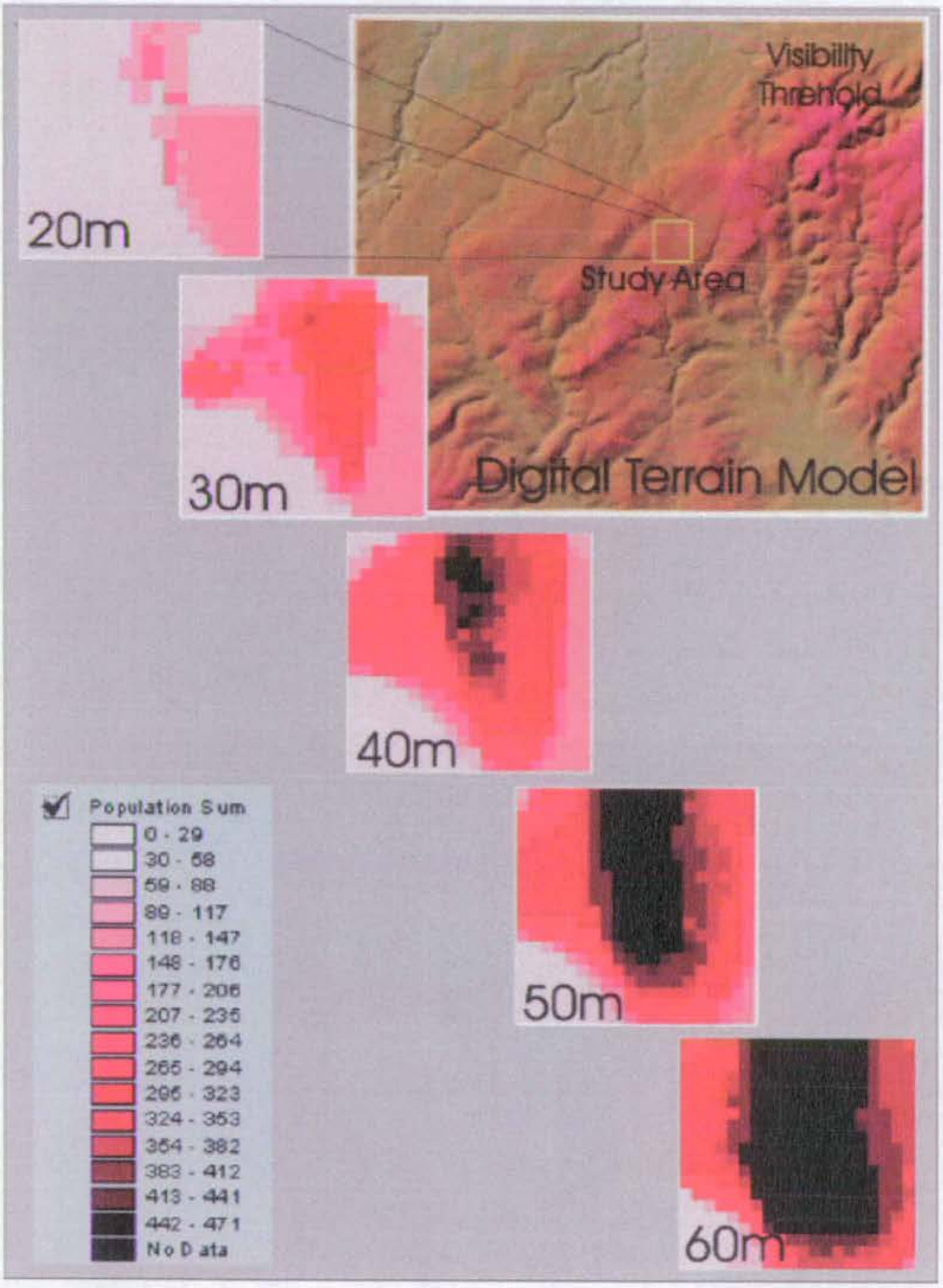

Figure 6.11: Maps of summed visual impact for Soutra Hill.

6.2 Shadow Flicker

Shadow flicker results at positions in the proximity of a WTG when the sun is directly behind the rotating blades in relation to the observer. A constantly changing shâdow is produced as the blades rotate, creating a visual nuisance.

ExWind calculates the positions surrounding a windfarm where shadow flicker is likely to occur. The maximum range of such flicker is user editable and normally taken to be no more than 1000m, Beyond 1000m reflection and diffusion of sunlight diminish the shadow intensity sufficiently to negate the problem, the WTG appearing as an object with the sun behind it.

ExWind allows user selection of any point within the shadow flicker area and calculates the number of hours per year when this phenomenon will occur, for example, in a house with a window facing towards the WTGs. The amount of time in the year that shadow flicker is likely also depends on the local sunshine characteristic stored in ExWind as the number of sunny hours per annum. This is user editable.

Normally periods of greater than 30 hours per annum [3] of shadow flicker should be avoided, either by resiting, briefly shutting down the turbine or providing blinds for the affected windows. Any of these mitigation measures constitute the external costs associated with shadow flicker.

6.2.1 Calculating the Sun's Position

In order to calculate which areas are affected over a specific period, the Sun's position in relation to the WTG and observer must be calculated.

The primary equations summarising the suns altitude and azimuth according to time and observer position are derived from Kepler's equations [174] with additional information from [175].

Declination (D_S: the latitude at which the sun is directly overhead) is calculated in Equation 6.1 where N_{day} is the day in the year.

$$D_S = 23.45 * sin[360/365 * (284 + N_{day})] \tag{6.1}$$

The sun's altitude angle (Al: the vertical angle in degrees above a horizon at sealevel) is described in Equation 6.2 where Lat is latitude, t the local time and t_{sn} the time of the local solar noon.

$$Al = sin^{-1}\Big[[cos(Lat) \times cos(t - \frac{t_{sn}}{4})] + [sin(Lat) \times sin(D_S)]\Big] \tag{6.2}$$

The sun's azimuth angle (A_z: the horizontal angle in degrees taken from due south) is

[3] Based on a a German court case.

calculated in Equation 6.3 where Lat is the local latitude.

$$Az = cos^{-1}\left[\frac{sin(Al) \times sin(Lat) - sin(D_S)}{cos(Al) \times cos(Lat)}\right] \tag{6.3}$$

As ExWind utilises the UK OS grid coordinate system (a modified transverse Mercator (TM) system), coordinates must be accurately converted to polar longitude and latitude for the sun angle calculations. The algorithm in ExWind uses a power series method and may be described as a standard reference implementation [176]. The maximum errors derived during conversion are found to be insignificant at less than thirty seconds.

Figure 6.12 illustrates an ExWind plot of an area likely to suffer from shadow flicker; individual numbers at user selected points on the plot denote the total time of shadow flicker likely (hours per annum) for that position.

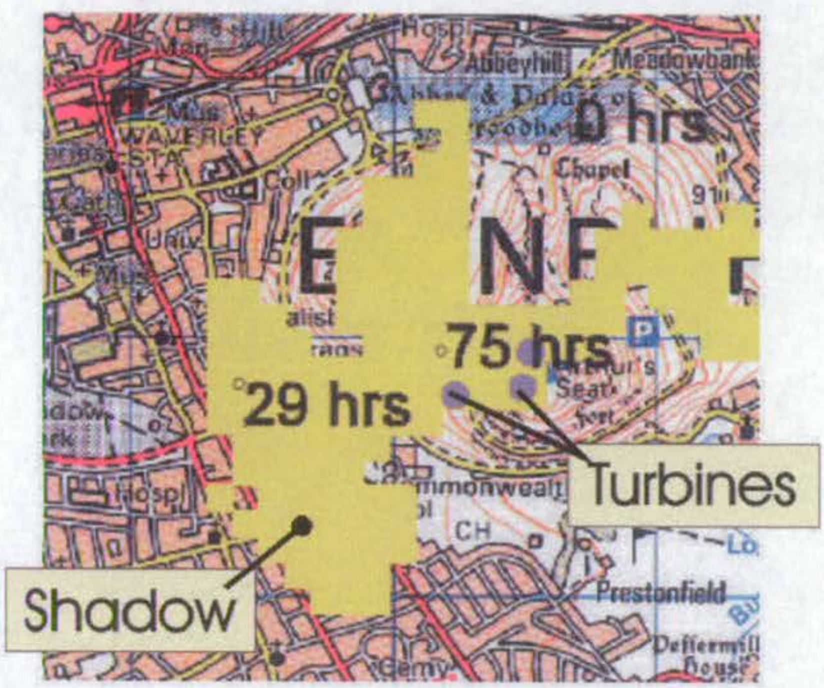

Figure 6.12: ExWind plot of likely shadow flicker from 3 turbines.

6.3 Noise

Several models are available for calculating noise emissions from a particular source. The required factors when calculating sound emissions may be identified as:

- Atmospheric absorption.
- Ground effects.
- Meteorological effects.
- Barriers.

The former two are of greater significance as meteorological effects are of lesser significance outwith close proximity to a windfarm, specifically due to the higher levels of background noise in windy conditions, and the necessity that barriers producing any noticeable reduction in noise would be sited impractically close to the WTG.

6.3.1 Acoustic Noise Models

The widely recognised IEA model [177] is based solely on atmospheric absorption and a highly reflective ground surface. It generally results in a small systematic overestimate compared to models such as CONCAWE [178] which take absorption into account. ExWind improves on the general IEA model by incorporating basic ground absorption from the CONCAWE model. Figure 6.13 illustrates a ground attenuation curve [179] as utilised in ExWind. Long range ray tracing techniques are unnecessary as the level of noise at these distances is negligible.

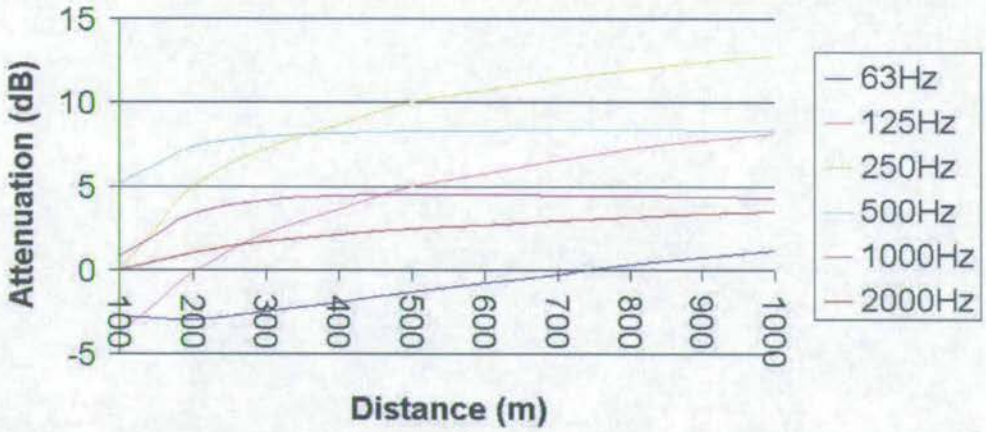

Figure 6.13: Acoustic noise ground attenuation curves (63-2000Hz).

6.3.2 Deriving the Background Noise Level

Initially, the background noise is measured at various positions around a potential wind site by means of a sound pressure level meter in accordance with [180] [181] and the results input to ExWind. ExWind then interpolates these data points to produce a surface map of the background noise levels in dB(A) across the entire study area. ExWind supports two suitable interpolation methods derived from [182].

1. Spline regularised.
   This entails sampling known noise data from a number (user selected) of points surrounding the position in question. A weighting of the third derivatives of a surface curvature minimisation for the known points is used to allocate a new value to the position in question.

2. Inverse distance weighted.
   This allocates a new value to a position by taking a number (user selected) of known noise data points within a set distance whose significance to the overall result depends on the exponent power of the intervening distance to the new position.

Figure 6.14 illustrates the background noise input dialogue displayed after a map point has been chosen by user map interaction. The map in the background is the interpolated background noise map.

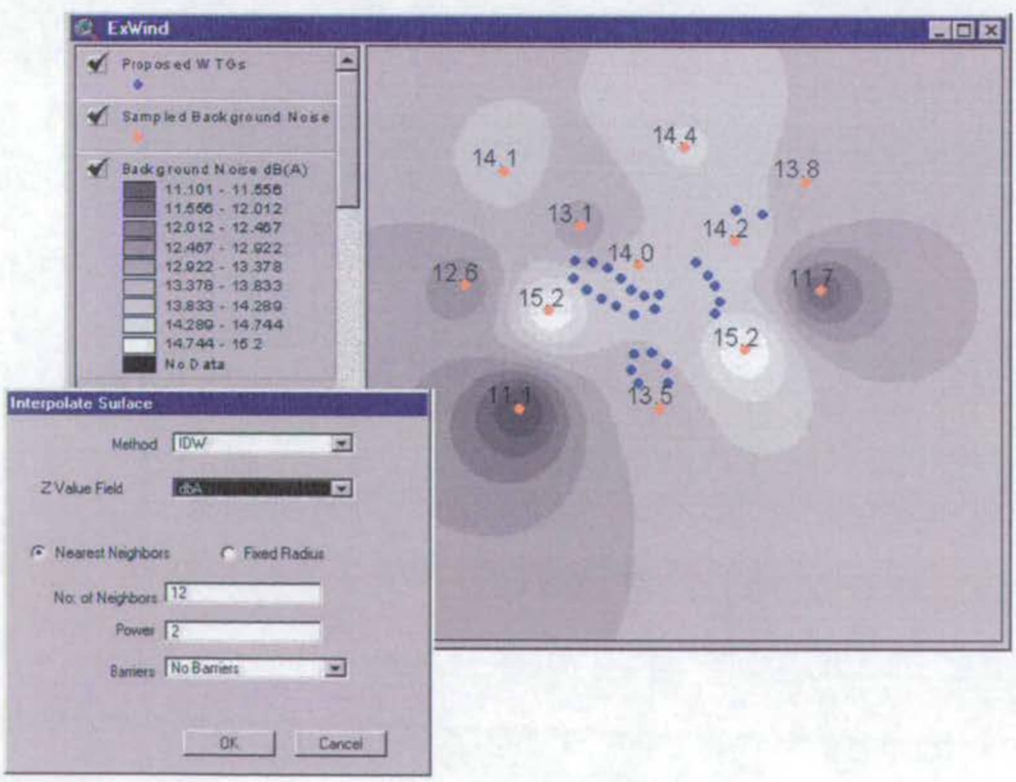

Figure 6.14: Background noise interpolation and resultant map.

6.3.3 Calculations for Acoustic Noise Levels

The specific WTG manufacturer certified noise level is used to calculate the noise emission to the area surrounding that WTG by use of the simplistic inverse square law including air attenuation [177] and ground attenuation [179]. The observed noise level from a WTG (L_p) is detailed in Equation 6.4:

$$L_p = L_w - 10.log_{10}(2\pi) - 20.log_{10}x - 0.05x + A_g(x) + G_g(x) \qquad [dBA] \quad (6.4)$$

where x is the distance from a noise source of power L_w, $A_g(x)$ and $G_g(x)$ being the air and ground attenuation functions respectively. The observed total sound level ($L_{p,total}$) from N WTGs at any point is derived as Equation 6.5.

$$L_{p,total} = 10.log_{10} \sum_{i=1}^{N} 10^{\left(\frac{L_{p,i}}{10}\right)} \qquad [dBA] \quad (6.5)$$

The total observed WTG noise level is summed with the background noise level to produce the observed noise level in Equation 6.6 where $L_{background}$ is the associated background noise level at the observer.

$$L_{obs} = 10.log_{10}\left[10^{\frac{L_{p,total}}{10}} + 10^{\frac{L_{background}}{10}}\right] \qquad [dBA] \quad (6.6)$$

Allowance is made for the time of day and non-operation of the WTGs. Between 10p.m. and 7a.m. a 10dB(A) penalty is adopted in Equation 6.7.

$$L_{tod} = 10.log_{10}\left[\frac{15}{24}10^{\left(\frac{L_{obs}}{10}\right)} + \frac{9}{24}10^{\left(\frac{L_{obs}+10}{10}\right)}\right] \qquad [dBA] \quad (6.7)$$

If the windfarm is taken to operate 70% of the year, Equation 6.8 describes the noise observed where $L_{tod,obs}$ is the observed WTG noise corrected for the time of day and $L_{tod,bgnd}$ is the observed background noise corrected for the time of day.

$$L_{year,obs} = 10.log_{10}\left[7^{\left(\frac{L_{tod,obs}}{10}\right)} + 3^{\left(\frac{L_{tod,bgnd}}{10}\right)}\right] \qquad [dBA] \quad (6.8)$$

6.3.4 Valuation of Changes in Acoustic Noise Level

It is possible to provide a valuation of the noise increase due to the proposed WTGs using similar CV methodology as that for the visual impact costing, the future increase in noise level being calculated by ExWind and simulated using VRML to spatialise the sound from multiple WTGs. In practice, the correct noise levels created are of a low magnitude, accurate reproduction being extremely difficult and inapplicable outwith a 350m radius of a modern WTG. Siting of a WTG at distances within 350m of habitation is avoided in the UK.

To provide the monetary valuation without a CV study the noise depreciation sensitivity index (NDSI) [184] method has been adopted. The NDSI is based on studies utilising hedonic pricing within the UK and defines a specific depreciation in house prices with increase in noise (dB(A)). Its advantages over other methods are set out in [183]. Equation 6.9 describes the annual value of noise (AVN).

$$AVN = \sum_{habitation} \left(L_{year,obs} - L_{tod,bgnd} \right) \times N_{houses} \times A(P) \times NDSI \tag{6.9}$$

Where N is the number of houses, A(P) the local annuitised average house price, and the NDSI which is taken as that cost associated with the noise [184].

The transferability of such a study to rural areas and particularly WTGs may be prone to error, but, due to the relatively low levels of noise from modern WTGs and their siting at a distance from residential areas, this value is acceptable as an upper limit.

6.4 Ecology

As discussed in Chapter 4 there is as yet no accepted method for the realistic quantification of the external costs directly associated with loss of flora or fauna. UK impacts are limited due to careful consideration during site selection and design to avoid problems with the necessary EIA.

A GIS is an excellent tool for describing any local ecological features and parameters: the reader is referred to [185] for an example of an ecological expert system utilising GIS. ExWind does not contain a specific methodology for quantification of ecological cost as the development of such a methodology is beyond the scope of this work. However, any ecologically sensitive area may be set apart as unsuitable for development as dictated by the precautionary principle, assigned an external cost, or the cost of the relevant mitigatory measures input. These ecological cost features are then considered when optimising possible development sites.

ExWind also provides a tool that dispatches a stand-alone application containing a map of the development area under consideration. This may be emailed as an attachment to interested or expert parties who may label and mark areas of important ecology before returning the map to the developer to be input into ExWind. Figure 6.15 illustrates the emailed application.

6.5 Electromagnetic Interference

As noted in Chapter 4, EMI may be a significant problem produced by a windfarm. Strictly it should not be included as an external cost but rather a development cost as mitigatory measures are required by the relevant authorities.

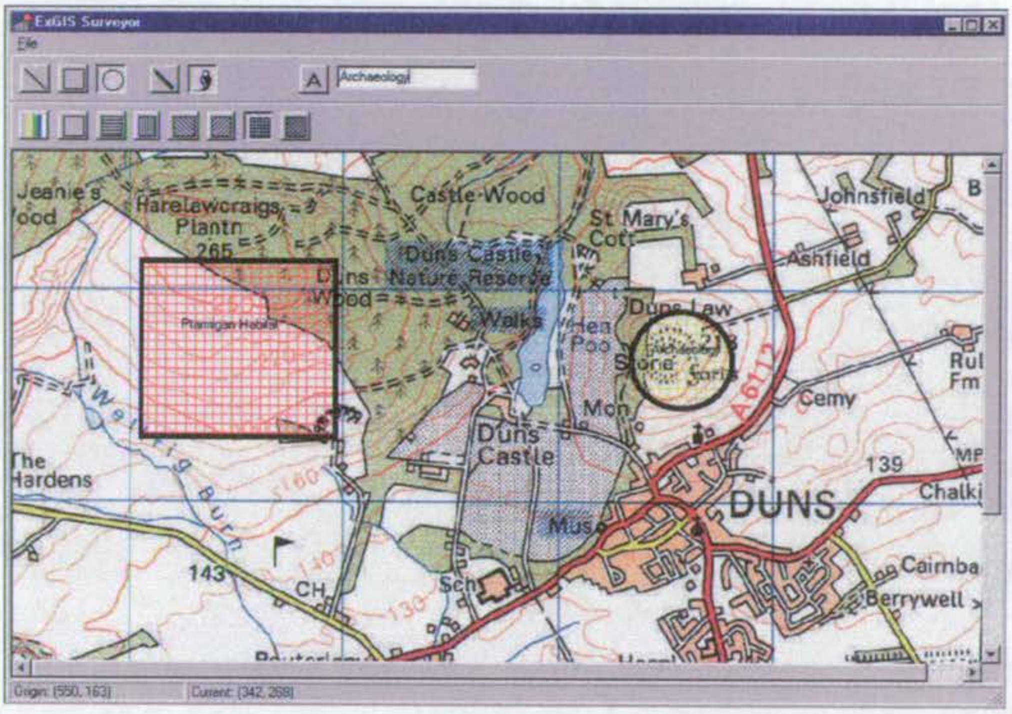

Figure 6.15: The ecology survey map application.

ExWind calculates the area of undesirable interference for terrestrial television signals or specific line of sight (LOS) systems from any number or types of horizontal WTGs thereby allowing expert advice to be sought to provide mitigatory measures. The costs incurred by the necessary mitigatory measures may be included in the financial analysis.

6.5.1 Radar Cross-Section

The radar cross section varies between the back-scatter [4] and forward-scatter [5] regions and is given by Equation 6.10:

$$\sigma = 10 \times log_{10} \frac{2\pi a L^2}{\lambda} \qquad [dBm^2] \tag{6.10}$$

where a is the radius of the WTG blade cross-section, λ the affected signal wavelength and L the blade length.

The metal roots of the blades are considered to cause the interference in the back-scatter region while the entire blade causes that in the forward-scatter region. The blades being approximated as cylinders, the appropriate values for each are entered in Equation 6.10

[4]Wave scattering in front of the blades relative to the signal source.

[5]Wave scattering behind the blades relative to the signal source.

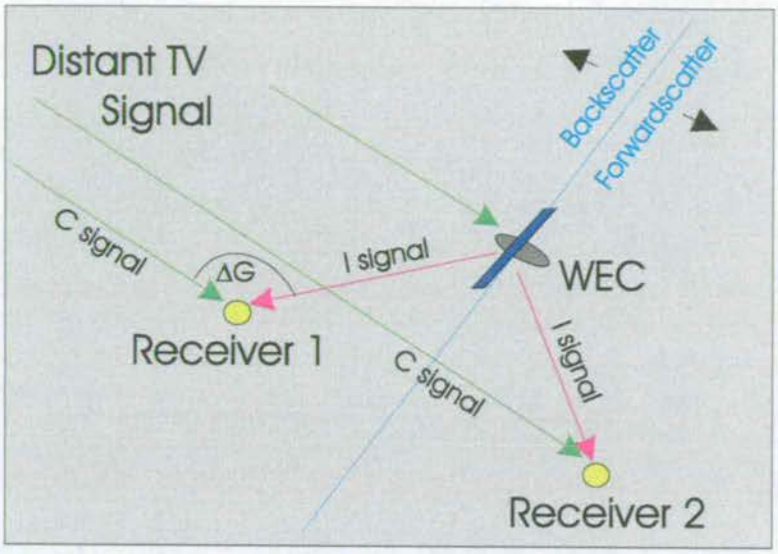

Figure 6.16: Electromagnetic Interference.

6.5.2 Calculation of EMI

Basic equations relating the geographical distance from a turbine to a receiver may be derived. Figure 6.16 clarifies. Equation 6.11 describes the general interference, while Equation 6.12 (the specific implementation of Equation 6.11) describes the interference in the back-scatter and forward-scatter regions [186].

$$\frac{C}{I} = 10log_{10}4\pi + 20log_{10}x - 10log_{10}\sigma + A_2 - A_1 + A_x + \Delta G \qquad [dB] \quad (6.11)$$

where ΔG is the directivity of the receiver, C is the transmitted signal, I the interfering signal, x the distance from the turbine, A_x the additional interference path loss from the obstacle to the receiver, A_2 the additional interference path loss from the transmitter to the obstacle and A_1 the additional transmitted signal path loss from the transmitter to the receiver.

Assuming the worst case where no constructive interference occurs:

$$A_1, A_2 and A_x = 0dB$$

$$\frac{C}{I} = 11 + 20log_{10}x - 10log_{10}\sigma + \Delta G \qquad [dB] \quad (6.12)$$

6.5.3 Mapping the EMI Effects

The Signal to Noise Ratio (SNR) producing acceptable picture quality may be user defined within ExWind and is normally taken as greater than 39dB [186]. The acceptable

SNR is used as the EMI study threshold in ExWind to produce a map of areas affected by EMI as illustrated in Figure 6.17.

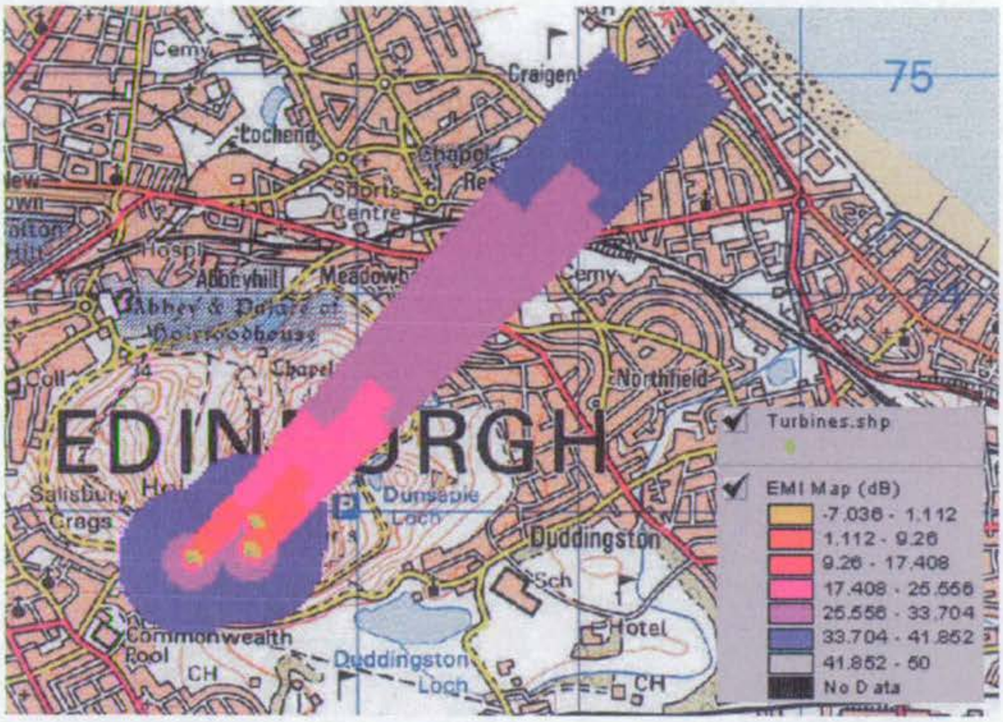

Figure 6.17: Example of the extent of windfarm EMI.

6.6 Externalities Dependent on Energy Production

Several externalities are directly dependent or readily definable by the amount of time the WTG operates and the work it does, *i.e.*, the kWh output.

6.6.1 Accidents

It is noted that there have been few accidents specific to windfarms to date. ExWind calculates this externality using the cost of accidents (public and occupational) per kWh produced over that time. The output in kWh multiplied by the cost per kWh due to such incidents then defines the likely external cost attributable. An ExWind dialogue allows user input costings if those costings derived in Section 4.6.6 (6.85×10^{-3}p/kWh) are deemed unsuitable in a specific context.

6.6.2 Emissions

A WTG offsets emissions, therefore an external benefit exists. Section 4.6.5 describes the difficulties in quantifying the cost of emissions from a fuel cycle due to the complexity of evaluating pathways and their monetary impacts. ExWind calculates the emissions offsets [6] of CO_2, SO_2 and NO_x per annum for the wind project. Figure 6.18 illustrates the ExWind emissions offset dialogue.

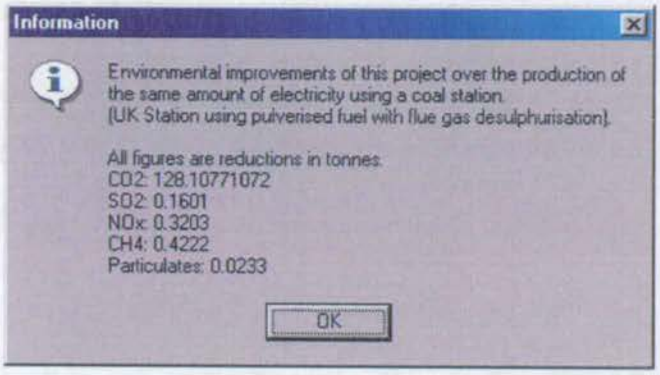

Figure 6.18: The annual emissions offset dialogue.

No specific monetary value is assigned by ExWind unless requested by the user. The costing estimates in Table 4.10 (CO_2 global warming damages) may then be selected from, along with acidification costs of 0.7 mECU/kWh [187] to determine the monetary benefits.

6.7 Access Road

ExWind uses OS road data to produce a least-cost route from the proposed wind farm to an existing road. Areas may be defined as being unsuitable to build on (for example, water features) or costly (for example, forest which requires clearing). Further limits may be set on the allowable gradient for an access road, cost multipliers for differing foundation costs dependent on ground type and user defined limits such as visibility from local habitation. Specific costs for the road are based on Table 5.3 scaled within ExWind as required by a user input map reflecting local conditions.

[6] As compared to the emissions output of the typically displaced coal fired power station using FGD.

6.7.1 Least Cost Routing

A raster ExWind access road cost is derived by use of ArcViews 'costdistance' function. The least cost algorithm [188] iteratively attempts to find the least cumulative cost route (through a path of raster cells) from the cell being examined to any segment of the existing road. This is repeated for all cells in the specified area producing the cumulative access road cost map. The least cost route from the existing access roads to any particular cell is recorded by means of an additional 'back-link' grid defining the direction of the least cost path. The 'back-link' grid enables the later recovery of the least cost route for a particular WTG project. A cumulative cost map for road access and the least cost route from the existing roads to four proposed windfarm sites is illustrated in Figure 6.19.

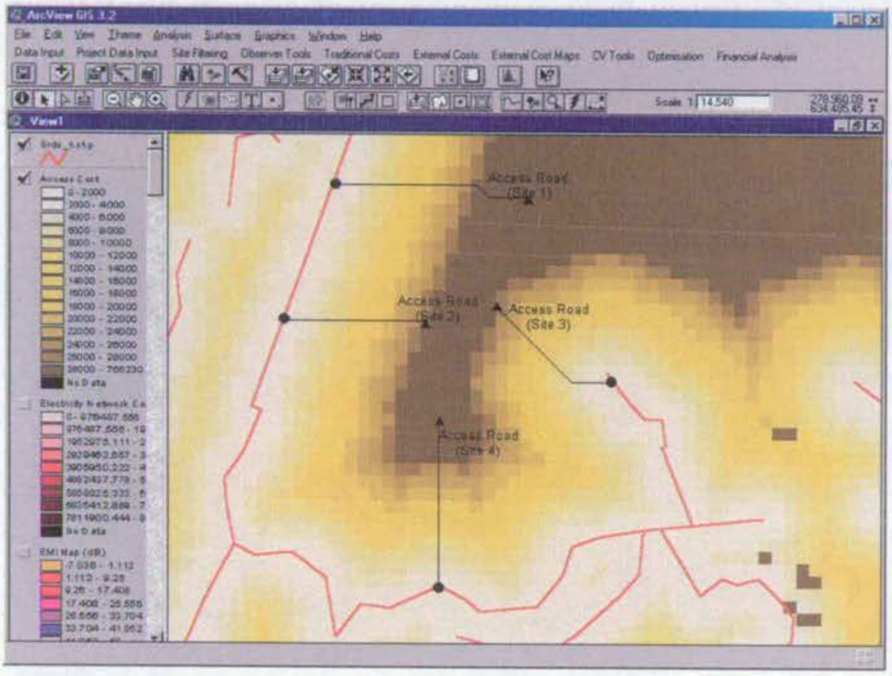

Figure 6.19: Access road cumulative cost map including least cost routes.

6.8 Electrical Connection

Existing distribution lines may be entered in ExWind by interactive on-screen use of the 'Electrical Network Input' tool. Estimated upgrade costs from the local network operator may be entered on the corresponding network sections (see Section 5.3.3).

In addition to any existing electricity network upgrades, new lines are normally required for connection between the existing network and the wind project.

6.8.1 Topographic Effects on Overhead Line Routing

A study was undertaken to determine the effect of gradient and local topography on new overhead line costs. A GA was modified to optimise a new section of overhead line with regard to minimum cost. The terrain elevation and sag clearance parameters are randomly generated according to the variation in slope allowable. The variation in slope may take any value in the range zero metres of added elevation for every horizontal metre to one metre of elevation per horizontal metre (*i.e.* a positive or negative gradient of 0^o to 45^o). The GA known as SPANS is included within ExWind.

The user editable parameters that are taken into consideration by SPANS when determining the effect of topology on new overhead lines may be listed as:

- The minimum line to ground clearances (B.S.1320: road crossings (7m), ground inaccessible to vehicles (5m) and other positions (6m) [189]),
- the maximum and minimum allowable span,
- pole heights ranging from 8m to 17m (B.S.1990) [190],
- the use of curves defining the cable sag [7] due to maximum temperature (maximum sag) and minimum temperature (possible uplifting),
- the cost ($\pounds\mathrm{m}^{-1}$) of overhead line,
- the cost ($\pounds$) of the specific pole.

The GA outputs the maximum distance achievable at the minimum cost per metre for a user selected number of trial runs. Each run is for a specific random ground profile to determine the effect of slope on cost and spanable distance. The results for 1000 random ground profiles (possible slopes) are summarised in Figure 6.20 [8].

It may be concluded from this particular study that there is no significant difference in the maximum distance spanned between successive distribution poles with change in topography. Undulating topography can provide a greater available span advantage given by local topological maxima. The most efficient use of resources (cost of poles and overhead line) is, however, slightly affected by the ground topology.

The effect of topology on the overall project cost is a function of pole and line costs which vary between locations. ExWind therefore allows SPANS to categorise the cost of building a new overhead line based on the local cost characteristics. The cost categories are dependent on slope which may be calculated from the DTM. A cost multiplier may therefore be assigned to all possible overhead line cells dependent on the slope in those cells.

[7] Default overhead line is a $0.025\mathrm{in}^2$ hard-drawn copper conductor.

[8] For poles of 8-17m, default conductor, spans of 20-50m.

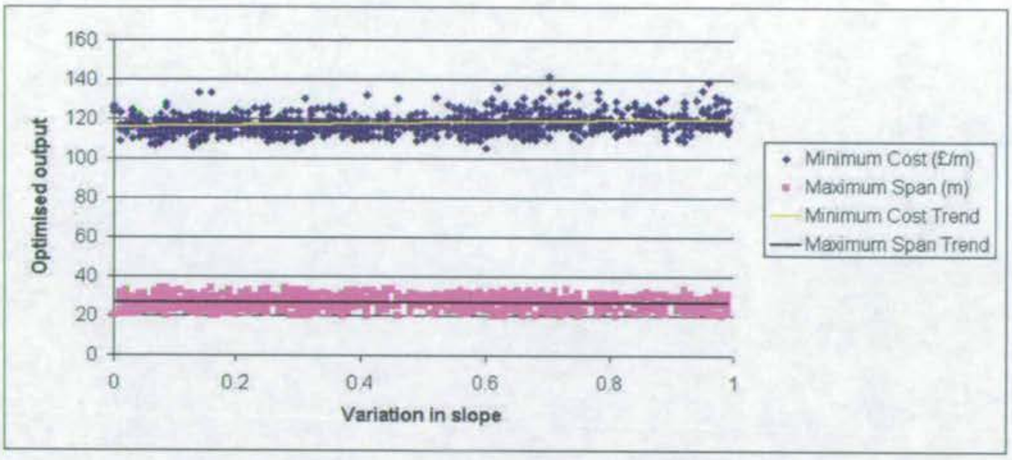

Figure 6.20: Comparison of overhead line cost over varying terrain.

These results broadly affirm a previous study [191] stating that the effects are minimal; however, the local costs may be accurately evaluated with the GA technique.

6.8.2 Other Costs and Least Cost Routing

Further overhead line cost multipliers may be manually inserted into ExWind, defining areas through which extra cost will be incurred when routing a line (e.g. marsh) and areas designated as costly from an external basis (e.g. visibility).

The least-cost route taken by the electricity lines from the windfarm to a point of connection on the existing network is determined in a similar manner to the access road, except significant costs associated with the required upgrading of any existing network (as estimated by the local network operator) are also taken into account. The optimum combinational route accounting for the lowest cost of new line and the lowest cost due to an existing line upgrade is returned.

An option to include an underground cable in the vicinity of the windfarm is provided. This automatically defines the extent to which underground cabling should be used dependent on:

- visibility to local population,
- minimum distance from the windfarm,
- minimum height below the windfarm.

The new line and cable costs are calculated on a simple per meter basis as set out in Section 5.3.3.4. More detailed quantification is possible but unnecessary at this stage.

6.9 Cost Minimisation

The user selected ExWind derived cost maps are input to the GA WTG layout solver along with project relevant data as illustrated in Figure 6.21. The GA solver produces the optimum WTG layout with consideration of traditional costs, or both traditional and external costs. Any form of layout (random, regular grid or linear row) may be selected.

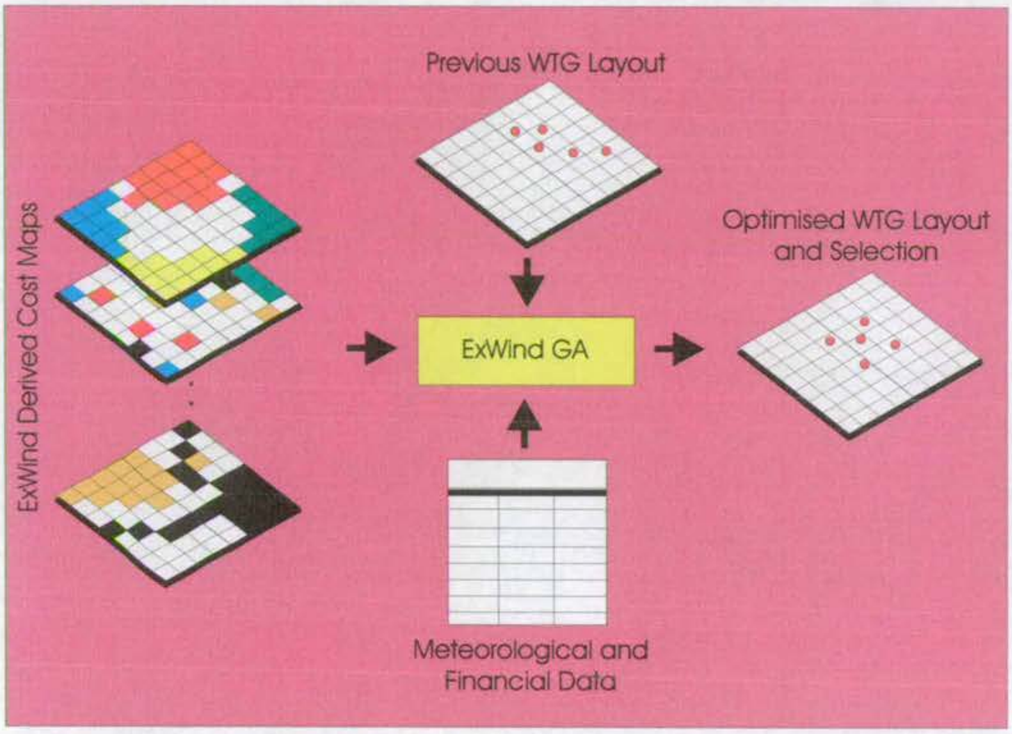

Figure 6.21: Data flow to and from an ExWind GA.

6.9.1 GA User Interaction

Figure 6.22 illustrates the GA parameter page of the ExWind GA application.

Further tabbed pages provide options for solution of the layout problem:

1. Simulation: options to run or close the GA application. When closed, all WTG positions derived by the GA are returned to the GIS and a map layer of the new WTG positions is produced and displayed.
2. Genetic Algorithm: parameter setting of the population size, number of generations, probability of crossover and probability of mutation.

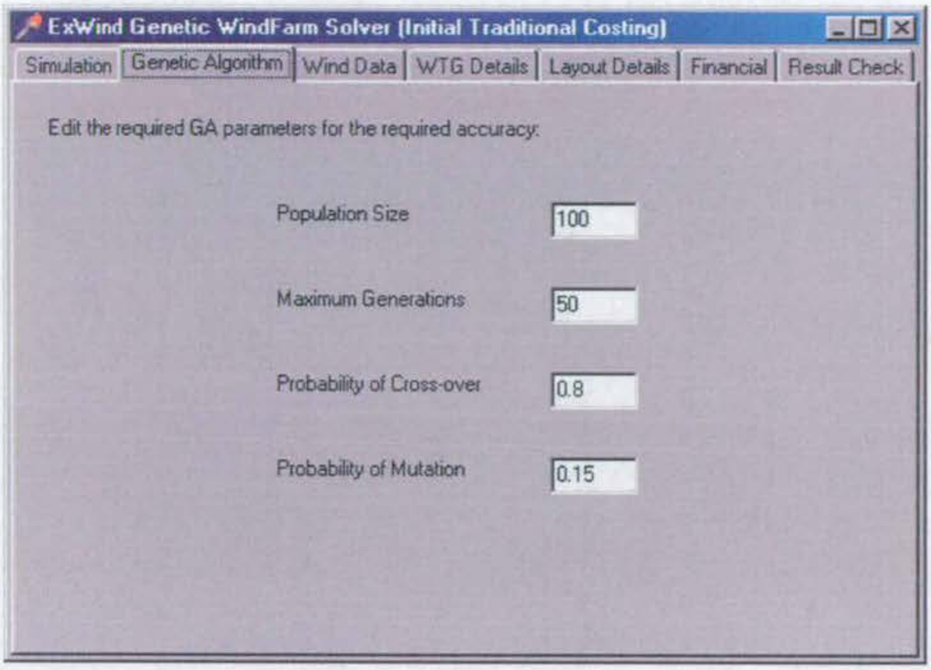

Figure 6.22: ExWind Genetic WTG layout optimiser (GA parameters page).

3. Wind Data: editable display of the relevant wind rose, height of wind measurements and roughness length.

4. WTG Details: display of all WTGs contained within the WTG database from which may be selected those applicable to the study in question. All may be selected, ExWind subsequently determining optimal WTG choice.

5. Layout Details: minimum and maximum WTG separation distance may be set along with a choice of inter-WTG infrastructure costings and the wake model parameters. Details specific to the type of layout may also be entered (for example, the aspect ratio of a regularly shaped grid layout or the maximum bend angle between WTGs in a semi-linear array). Heuristic initialisation of a possible WTG layout from existing ExWind layouts is included as an option.

6. Financial: the financial parameters of discount rate and p/kWh for electricity sold are retrieved from the financial module and displayed. These may be user edited, all updates being registered by the financial module.

7. Result Check: this page allows the user to view the GA returned best layout of WTGs as a list. The associated project NPV is also displayed. This allows the user to reset the GA parameters and continue optimisation if required.

6.9.2 GA Cost-Benefit Optimisation

The kWh's produced per annum are derived from the calculated wind velocity (Equations 4.6 - 4.14), the WTG power curve (Equation 4.15) and the analytical solution in Equation 4.17. The calculation of energy (kWhs) produced is used as the basis for the monetary benefit from the wind project, all other costs being sourced from the relevant functions. The result to be maximised by the GA fitness function is profit, specifically NPV.

ExWind attempts the benefit maximisation for all suitable WTGs, all suitable tower heights and all suitable WTG positions. The specific area encompassing all possible WTG positions is assigned and all required data produced as a series of GIS cost maps covering the geographical positions to be accounted for. These raster GIS cost maps are passed to the GA as arrays defining cost for any possible WTG position. The GA examines the effect of WTG position and layout on project profitability. Initially the costs incorporated are the traditional factors, but subsequent to the formulation of a suitable layout by these traditional methods all externally derived costs are included. The maximum financial benefit gained by producing electricity is therefore that WTG layout solution providing maximum NPV upon inclusion of all cost factors.

6.10 Financial Analysis

All monetary cost and benefit components derived by ExWind are summarised and evaluated within the financial analysis modules.

6.10.1 Financial Analysis Modules

Figure 6.23 illustrates the overall financial summary dialogue within ExWind to which all project economic data is returned.

All proposed WTG details (including all costs and kWh output) are listed and user editable. Similarly the ExWind derived electricity and road network costs are displayed. Any combination of the proposed WTGs may be selected for financial appraisal.

The basic financial conditions applicable to the current wind project may be set, including the applicable project discount rate, the likely availability of the WTGs and the selling price for the electricity produced.

Error bounds may be entered to reflect uncertainty in the external costs and project conditions. This enables the user to undertake a simple sensitivity analysis to determine the sensitivity of investment outcome with variation in project circumstance.

The financial evaluation dialogue activated from the aforementioned financial summary dialogue is illustrated in Figure 6.24. The financial evaluation provides a table of cash-

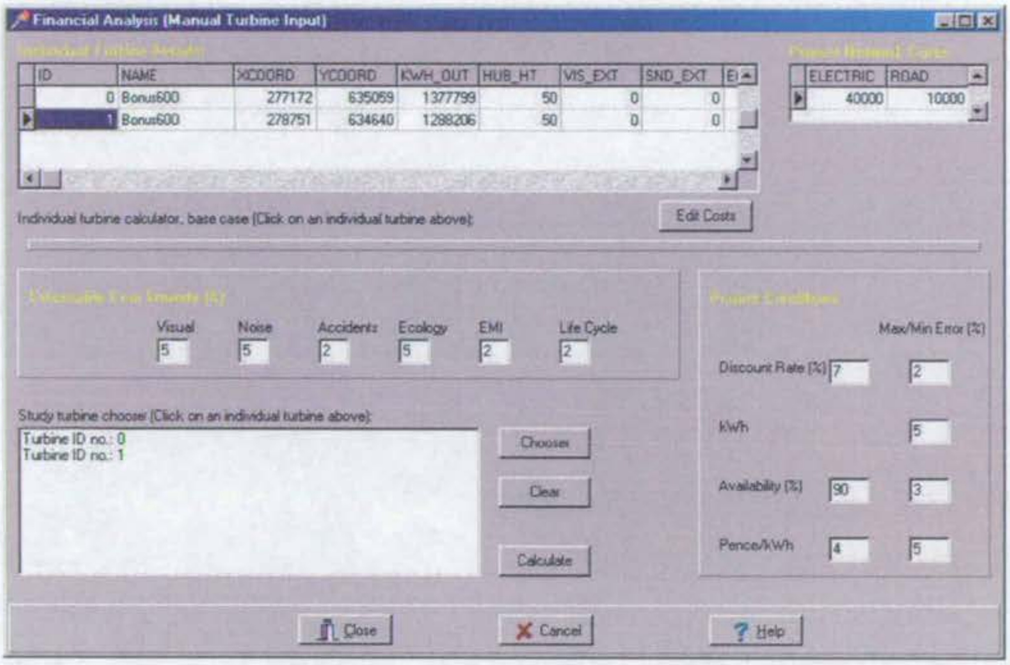

Figure 6.23: ExWind financial summary and parameter selection dialogue.

flows, calculation of net present value (NPV), internal rate of return (IRR), payback (PB) and graphical output of the cashflow over the project lifetime. Each of these functions is undertaken for a base, best and worst case according to the current project. The three cases are based on the definition of the likely error values.

6.10.2 Discount Rate and Taxes

The discount rate selected reflects the cost of capital which in turn reflects the likely interest, inflation and loan rates. The discount rate is made up of a combination of the real interest rate (interest rate minus inflation rate) and the finance rate applicable. It is assumed that inflation is common to all features as price moves are broadly in parallel over time. The project should be discounted at a number of different discount rates in order to gauge the effect on financial viability. The discount rate is also adjusted for risk, a higher return being desirable to compensate for the increased risk of project and investment failure.

Taxes may be included but are ignored in the default calculation. Normally the favourable tax depreciation regulations allow a higher return on investment as the deduction of loss of asset value is faster than the actual devaluation in real terms.

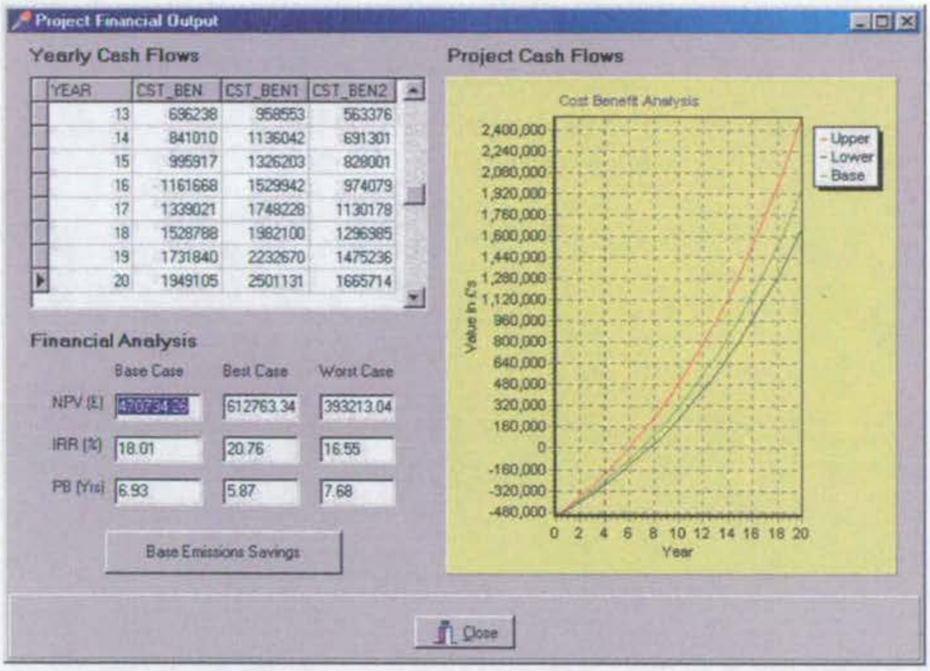

Figure 6.24: ExWind financial evaluation dialogue.

6.10.3 Cashflows

The project lifetime is taken as the projected WTG lifetime of 20 years. The costs are calculated from the specific WTG costs including externalities as set out previously, while the benefit is calculated from the electrical output with the relevant price paid per kWh. The discounted cashflows (discounted revenue minus cost) form the basis for the NPV, IRR and PB analysis.

6.10.4 Net Present Value (NPV)

NPV returns the value (in £) to an investor of the project over and above what would be made by investing at the investors marginal rate. The investor marginal rate is usually the opportunity cost of capital. NPV forecasts all future net cash flows for the project being considered and discounts them to their present value using the investors cost of capital as the discount factor. NPV may be summarised as:

$$NPV = \sum_{t=1}^{t=n} \frac{A_t}{(1+r_d)^t} \tag{6.13}$$

where A_t is the net cashflow for period t, r_d is the financial discount rate and t is the specific year of an n year project lifetime. All projects retaining a positive NPV are accepted as wealth creating.

6.10.5 Internal Rate of Return (IRR)

IRR attempts to find the discounted rate of return on investment, or the discount rate that produces an NPV of zero (break even). IRR is found by varying the discount rate (r_d) in Equation 6.13 to produce an NPV of zero. The ExWind algorithm uses a Newton Raphson iteration method for an efficient solution. The returned IRR may be compared with the cost of capital, and if greater the project is accepted as profitable.

6.10.6 Summary

The NPV method is most reliable as an indicator of investment viability as it always indicates the optimal investment alternative. It is therefore noted that NPV is an absolute measure whereas IRR is a relative measure. The GA optimisation is therefore based on NPV.

ExWind provides a flexible mechanism for various financial analyses of a project or part thereoff including analysis of sensitivity.

6.11 Summary

This chapter has described the detailed functionality of ExWind in quantifying all relevant project costs and benefits, both traditional and external, as monetary values.

Visual impacts are quantified by use of a new VR and photomontage technique producing high quality visualisations. This increases the accuracy of the CV techniques used to quantify monetary impacts. The CV technique has been discussed as to its suitability and methodology.

Acoustic noise costing is carried out by use of a new hybrid model based on the IEA and CONCAWE models. This predicts changes in the level of noise due to a specific development from which a cost may be assigned from previous noise costing studies.

ExWind accounts for EMI and shadow flicker by specific algorithms relating geographical and physical parameters to impacts. Costs are then assigned.

All other relevant external costs (ecological, emissions, accidents) are calculated as required by the user. Costs or benefits for emissions and accidents are based on previous experience within the wind industry.

All traditional costs and benefits are also included from which an initial WTG layout is derived. External costings are then included and the project re-optimised by use of a GA according to all costs and benefits from the perspective of maximising NPV. This result may then be further tested by external costing if desired until no further optimisation of the project is possible.

Chapter 7

ExWind Example Analyses

Verification of the impact pathway methodology encapsulated in ExWind requires field testing with real data and responses from those affected. Evaluations were carried out for a number of studies which are described in this chapter. The two primary studies relate to:

1. the quantification of externalities particular to an existing windfarm,
2. the quantification of externalities applicable to a proposed windfarm and the subsequent true cost optimisation.

7.1 Selection of Study Areas

Several windfarms exist in Scotland for which a suitable existing windfarm study may be undertaken. However, when evaluating a proposed windfarm, it was regarded as important that the area selected and methodology used must not prejudice local inhabitants concerning any existing windfarm development plans. Therefore, to avoid conflict, it was decided to select an area where no development is currently under consideration.

7.1.1 Selection of an Existing Windfarm

The area selected with an existing windfarm is Hagshaw Hill, South Lanarkshire (UK grid reference 279300, 630700). Hagshaw Hill, Scotland's first windfarm, has been operational since November 1995 and consists of 26 Bonus 600 WTGs.

The rationale for choosing Hagshaw Hill for this study consisted of the relatively high population density in the surrounding area (the towns of Douglas, Smallburn, Muirkirk and Coalburn) which may derive significant externalities, and the five year period of exposure to the development producing relevant local experiences.

7.1.2 Selection of a Possible Windfarm Site

The area selected (by ExWind) for the second study was initially that of Soutra Hill in East Lothian, however, it was subsequently discovered that a planning proposal existed for this site. Further evaluation within ExWind of the area surrounding Douglas, South Lanarkshire yielded Pagie Hill (UK Grid coordinates 284834, 628565) as a suitable site on which to consider development.

7.1.2.1 Issues Related to the CV Study

In order to retrieve meaningful valuations from the local population it is a necessity that they believe the project is likely to occur even if for a theoretical exercise. To avoid local rumours and action against a perceived project a number of measures were implemented.

1. The CV survey was carried out over a short period (two days) to avoid misleading local discussion and rumour.

2. Those surveyed were informed that a new technique was being tested and that post-survey all outstanding questions would be fully answered.

3. The CV survey had a duration of approximately 30 minutes, at the end of which it was explained that the exercise was theoretical but useful and the reasons given.

4. A thank you letter to this end with contact details for any further queries was left with each person surveyed to allow for any further clarification if required.

The windfarm layout was then optimised according to the returned valuations and the original costings to complete the true-cost optimisation. A subsequent valuation was used to verify that the project had been improved and to check that the externality quantifications were of an acceptable accuracy. This valuation of the newly optimised windfarm was similar to the initial survey and undertaken shortly after the initial CV survey from a new (unbiased) population sample who knew nothing of the initial CV study. Belief in the reality of the project was therefore retained at all CV stages.

7.2 Verification of Algorithms

The study of an existing windfarm allows verification by field measurement of the ExWind functions producing externality quantification, specifically, the visibility algorithm and acoustic noise calculations. The EMI calculation has been verified in [194]. In addition the results from the algorithms defining the required infrastructure (access road and electrical connection) may be compared to the existing infrastructure design.

7.2.1 Initial Site Selection

Initially ExWind evaluated an area of East Lothian and returned the best areas for windfarm development. The parameters used in the ExWind search are recorded in Table 7.1. The site returned was Dun Law (UK grid reference 346000, 657600). A traditional cost-

Factor	Threshold
Windspeed	$> 7.5ms^{-1}$
Distance to access road	<3000m
Distance to electricity network	<5000m
Setback from habitation	>500m
Setback from forest	>300m
Setback from water features	>50m
Ecologically sensitive areas	AVOID
Designated areas	AVOID
Setback from radio transmitters	>1000m

Table 7.1: ExWind initial site filter parameters.

benefit evaluation of the proposed site at Dun Law yielded a positive NPV, confirming the choice of a developable site.

Further investigation revealed an anemometer mast at Dun Law and it was subsequently discovered that Renewable Energy Systems (RES) proposed to build a windfarm there. A study in the surrounding area with possible affect on public opinion was therefore deemed irresponsible. The automatic ExWind selection of a site currently under consideration by a commercial windpower company proves that the initial ExWind site filter is capable of producing realistic initial evaluations.

7.2.2 Visibility Analysis

The visibility analysis carried out for the existing windfarm at Hagshaw Hill (Figure 6.3) was verified at random points in a field study. The results are summarised in Table 7.2. Positions where mismatches occur between the calculated and observed number of WTGs are overestimates by ExWind. These positions are those affected by artefacts not included in the DTM (trees, new buildings, etc.), which result in a systematic overestimation of WTG visibility. The ExWind visibility calculation is therefore a worst case calculation resulting in a small overestimate of visual impact.

Corrections may be made to the DTM to include such features although this is a time consuming task without the use of automated photogrammetry from stereo pair photographs and a number of ground control points [195] . The use of digital photogrammetry techniques is costly and likely to be applied only in close proximity to the proposed windfarm. It is also argued that dynamic and changing landscape elements such as trees should not be included in visibility analyses to prevent unpredicted visual impacts after landscape element change. Therefore the ExWind visibility analysis is accepted as accurate.

UK Grid Reference	Calculated No. of Visible WTGs	Actual No. of Visible WTGs	Overestimate of Visible WTGs
284271,635431	26	26	0
283149,635049	26	25	1
281061,634428	0	0	0
281174,635966	25	0	25
280270,637815	26	20	6
280102,637609	26	20	6
279012,637056	0	0	0
279855,636906	0	0	0
280147,636047	24	23	1
280303,635977	24	24	0
280448,635851	24	24	0
283452,631004	15	15	0
283723,630954	19	19	0
283221,630351	14	14	0
282081,631019	2	2	0
282061,628693	24	24	0
281578,627232	26	26	0
283733,630838	19	19	0
281029,631632	20	20	0
284629,628882	26	26	0

Table 7.2: Results of Visibility Analysis Verification.

The ExWind VR created photomontages were tested to prove that they would create a realistic impression of the windfarm proposed. Photographs of the existing windfarm at Hagshaw Hill were taken, the WTGs removed, and replaced using the ExWind VR photomontage algorithm. The ExWind produced visualisations (uncorrected by the ExWind image manipulation tools) were then compared with the original photograph. The results match to a high degree, particularly at medium distances (500m - 3000m). An example set of the actual and simulated windfarm is shown in Figure 7.1.

7.2.3 Acoustic Noise

To confirm the ExWind sound calculations a study of the actual sound levels around the existing windfarm at Hagshaw Hill were undertaken. The background noise levels were measured at a time when no WTGs were operational. The resulting differences between the acoustic noise levels measured by a digital sound pressure level (dB(A)) meter at 14 stations proximal to Hagshaw Hill windfarm (averaged over a series of 5 observation periods) and the predicted levels are listed in Table 7.3.

Further observations in differing atmospheric conditions over an extended period should be made for a complete verification of the methods used, however the comparisons between the sound model (IEA-Concawe hybrid) and the actual measurements show significant agreement. The noise level estimations produce a root mean square (RMS) error of 3.09dB(A) and are in general an improvement on the IEA model which has a systematic RMS error of 4.5dB(A) at similar distances [192]. Therefore the acoustic noise model is accepted as appropriate.

Figure 7.1: Actual (top) and ExWind produced (bottom) scenes at Hagshaw Hill.

UK Grid Reference	Measured sound level dB(A)	Calculated sound level dB(A)	Absolute error dB(A)
278372,630916	22.1	20.9	1.2
278711,630972	52.8	50.1	2.7
278960,630878	53.7	49.0	4.7
278561,630436	31.2	27.9	3.3
279722,631288	50.0	45.9	4.1
279077,630406	52.1	49.4	2.7
279247,630795	51.2	50.2	1.0
279473,630794	45.1	41.0	4.1
279420,631164	45.6	43.1	2.5
279639,631322	54.1	49.2	4.9
279895,631202	41.1	45.1	-4.0
279072,630516	47.2	48.8	-1.6
280122,631016	29.0	29.2	-0.2
278689,631013	58.1	59.2	-1.1

Table 7.3: Comparison of calculated and observed acoustic noise levels.

7.2.4 Access Road and Electricity Line Routing

All relevant routing details were input to ExWind for the existing WTGs at Hagshaw Hill windfarm. The ExWind least cost routing tool was then implemented to return the best route applicable to the windfarm. The route returned and the actual route employed at Hagshaw Hill are illustrated in Figure 7.2. The ExWind results are noted to be very similar to the original human design. The raster resolution of the GIS data (50m) does, however, lead to sharp turns in the road rather than smooth bends. A higher raster resolution prevents this but increases processing time, the costing not changing significantly.

The route of the new electricity connection is determined by a similar cost-distance study as that used for access road routing but based on the over-head line and underground cable costs. The ExWind returned route remains similar to that existing in real life, also illustrated in Figure 7.2.

7.2.5 Wind Velocity and Energy Calculations

The wind data used in the studies is the NOABL [151] windmap of the UK at 45m above ground level and 1km resolution. The coarse 1km^2 resolution of the wind data implies that wind velocities are uncorrected for small scale local topography and local roughness characteristics (crops, hedges, trees etc.) or WTG wake implications. ExWind therefore defaults to the calculations set out in Section 4.2 to provide better wind velocity estimates at the required 2500m^2 resolution.

Validation of the wind velocity determination techniques and electrical energy output is by comparison with the analyses contained in the European Wind Atlas [193]. The ExWind calculated wind velocities and energy output for the example analyses match those predicted in the European Wind Atlas to within 3.7%, therefore the calculations

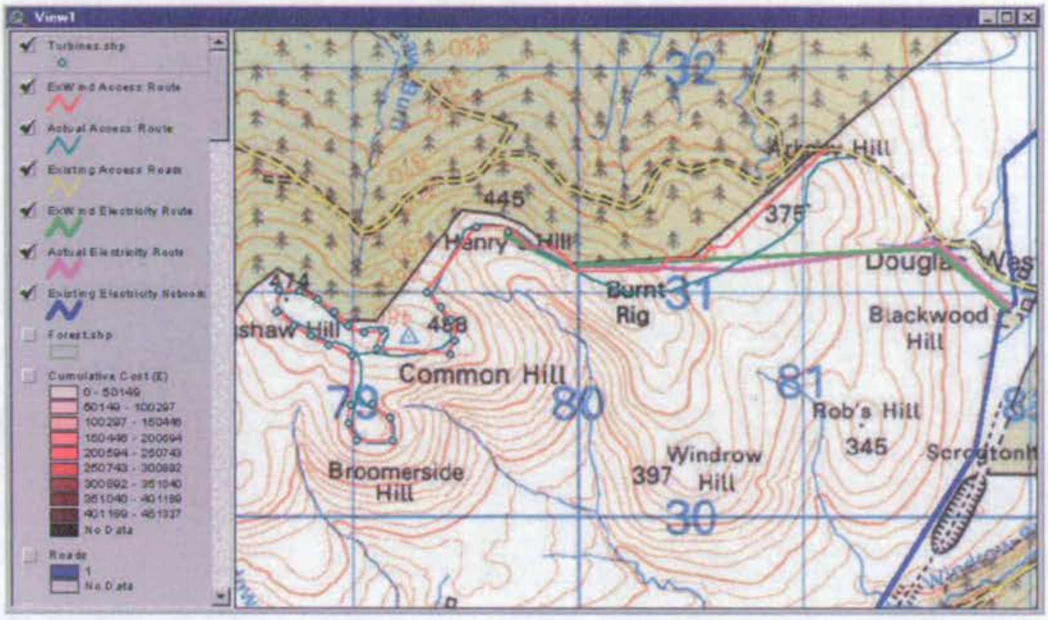

Figure 7.2: Actual and ExWind returned access road routes.

associated with the studies contained in this chapter may be taken to be sufficiently accurate.

7.3 External Costing of an Existing Windfarm

The evaluation of the externalities associated with an existing windfarm (Hagshaw Hill) produces a basis for considering the likely externalities imposed by a proposed windfarm. Comparative analysis with the externalities of a proposed windfarm may be made.

The population within a 10km radius of Hagshaw Hill wind farm was randomly sampled with a bias towards inhabitants in close proximity to the windfarm. The resultant population sample was surveyed both to evaluate the visual impact costs, and to confirm the externality costings associated with this site by ExWind.

Visual impact costing was undertaken by personal CV for each member of the sample population (42 respondents). The CV questionnaire was modified to reflect the cost of removing the wind farm due to its visual disamenity and to elicit the monetary value a respondent was willing to pay for this service (in addition to their normal electricity bill).

Further generalised questions regarding experience of the windfarm were asked of those completing the CV survey and an additional 48 randomly sampled respondents.

7.3.1 Results for an Existing Windfarm

The ExWind quantified externalities and the responses to the general questions indicating experience of a disbenefit (an external cost in qualitative terms) are reported in Table 7.4.

Externality	Derived total cost £	% of population disbenefited
Visual impact	10,632	5.0
Acoustic noise impact	0	1.1
EMI impact	0	1.1
Ecological impact	0	2.2

Table 7.4: Comparison of ExWind calculated externalities and those reported.

Visual impact is shown to be the most significant of the Hagshaw Hill windfarm externalities. A small but significant number of respondents reported that visual impact was a disbenefit, but, 83.3 % of those responding in this manner returned zero contingent valuations. The reasons most commonly given being that even though disproving of the visual impact it could be 'lived with' or it 'cost nothing'.

ExWind returned zero external costs for all other externalities due to the minimum distance of any WTG to the local population (2315m). A few respondents did, however, claim that the windfarm disbenefited them. Interestingly the same respondents lived at distances of greater than 5000m from the windfarm.

The generalised results in Table 7.4 closely agree with the findings of a Scottish Executive Central Research Unit survey published shortly after this study [196].

7.4 Design Optimisation of a New Windfarm

Following the rejection of the possible windfarm site at Dun Law (Section 7.2.1), a large area of South Lanarkshire was tested within ExWind. The same parameters recorded in Table 7.1 were used. A site on Pagie Hill (UK grid reference 284834, 628565) was returned, and is illustrated in Figure 7.3.

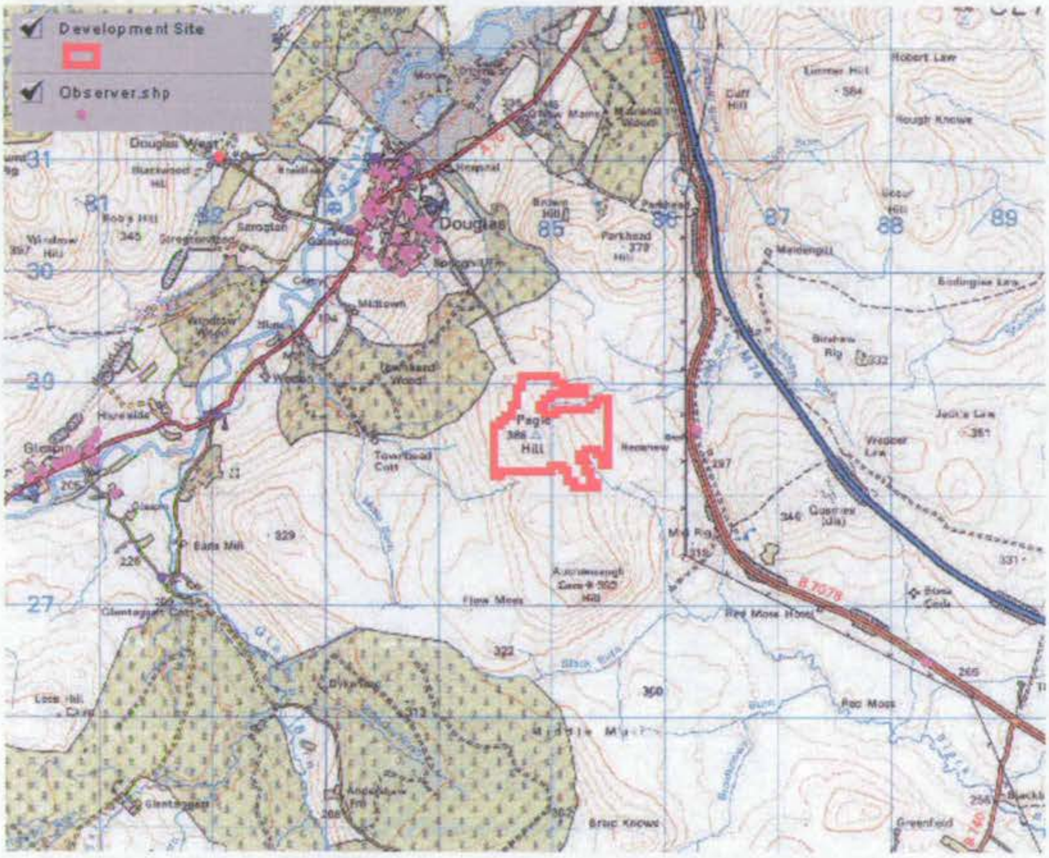

Figure 7.3: ExWind returned development site at Pagie Hill.

7.4.1 The Proposed Project

Pagie Hill is situated 2.5 km south-east of the town of Douglas. The landform is variable, settlement turning to moorland on higher ground beyond the planted coniferous forest. ExWind therefore recommends that a clustered development of between one and ten WTGs making up a single distinct landscape element is suitable. After consideration of the site and the ExWind development recommendation a development of 5 WTGs was chosen. The selected number of WTGs derived partially from ExWind advice is the only external project decision required from the user. All further project characteristics and optimisation are carried out by ExWind.

7.4.2 Parameters for Initial Traditionally Costed Layout

The initial layout from which local external cost relationships may be calculated is derived from a normal cost-benefit analysis accounting for all construction, operation, maintenance, and financial costs. ExWind derives these from the WTG databases, the financial parameters database and the derived cost maps for the new access road and electricity network. The wind map, road access cost map and the electrical connection cost map for the returned development area are illustrated in Figure 7.4. These cost maps represent continuous cost functions at $2500m^2$, $100m^2$ and $100m^2$ resolution respectively.

The WTG energy outputs are calculated using the relevant wind velocity map, wind direction rose, local topographical factors and the energy losses due to WTG wake interactions.

All major ExWind optimisation parameters used in this study are summarised in Table 7.5 [1].

7.4.3 Optimisation of the Traditionally Costed Layout

The traditional costing data is input to a traditional cost benefit analysis contained as the fitness function of the windfarm layout GA. In the case of Pagie Hill an initial best design WTG layout (Bonus 600 WTGs) was entered by use of ExWind's manual WTG input tools. This is the heuristic starting point for the GA. Although the GA does not require a starting layout this allowed a check to determine whether the GA could produce a layout better than a human design.

Figure 7.5 demonstrates a typical ExWind GA convergence for Pagie Hill. It can be seen that the initially entered manual WTG layout is not optimal (NPV of £920,395) compared to the layout to which the GA converges (NPV of £996,089). Optimisation of the various cost maps and project parameters together with the layout dependent interaction between WTGs is a non-trivial task and a human design is unlikely to be able to account for all of these in an optimal manner. It is notable that the convergence characteristic contains steps where the GA (by mutation and crossover) has rapidly discovered a significantly better WTG layout. Selected layouts at various points during the GA optimisation are illustrated in Figure 7.5, the red points denoting WTG positions within the yellow development area.

The final traditionally costed WTG layout is noted to face in the dominant wind direction and to have accepted greater electricity network cost and slightly increased access road cost in favour of utilising the higher windspeeds to the west of the development area. The optimal cost trade-offs for increased NPV have been made.

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[1] The average house price used in acoustic noise costing is derived from Glasgow Solicitors Property Centre local data, July 2000.

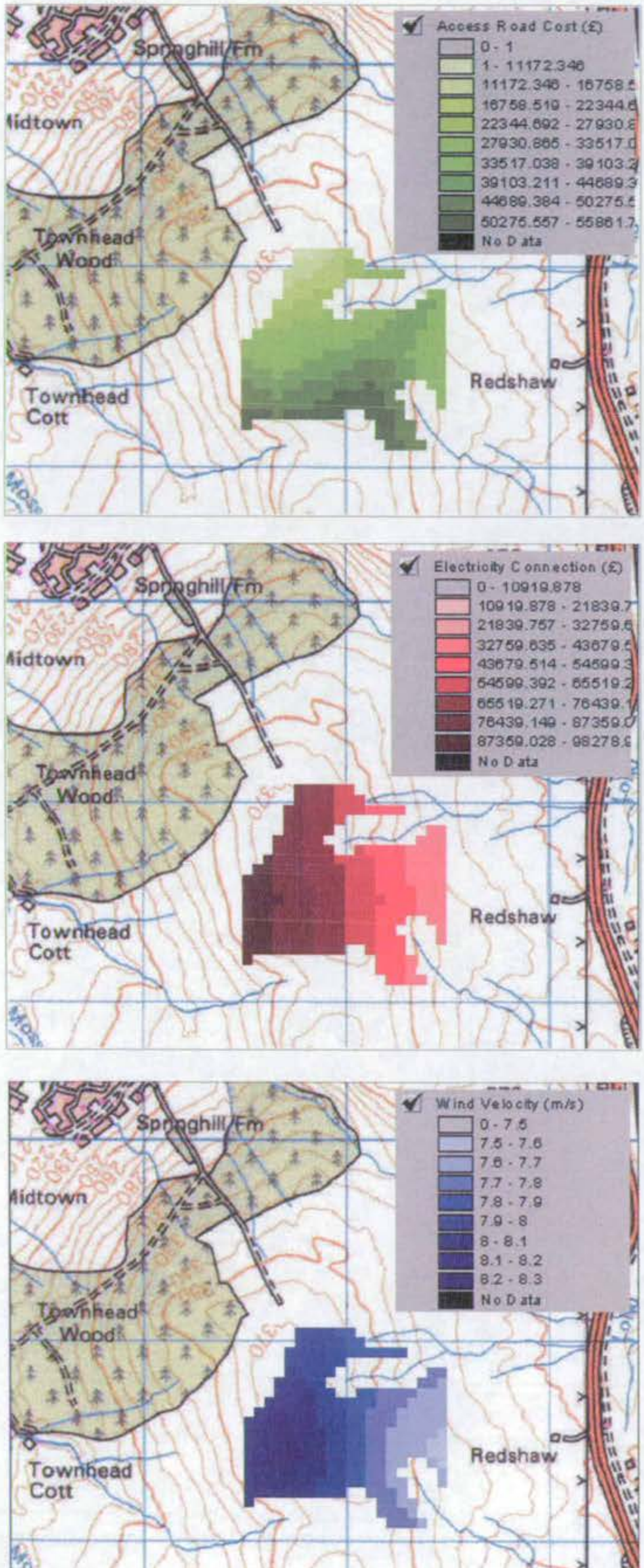

Figure 7.4: Pagie Hill development area: wind and infrastructure cost maps (top - access, middle - electricity connection, bottom - wind velocity).

Wind
Wind velocity: NOABL UK windmap, corrected to $2500m^2$ resolution based on local features
Directional ($0^\circ - 330^\circ$ in 30° sectors) probability (%): 7, 6, 5, 5, 3, 4, 6, 9, 13, 17, 14, 11
Measurement height: 45m
Roughness class: 2
Roughness length: 0.005
Genetic Algorithm
GA population size: 200
GA generations: 1000
GA crossover probability: 0.8
GA mutation probability: 0.15
Wind Turbines
Bonus 300: tower heights 40-50 in 10m sections, cost £100,000
Bonus 600: tower heights 40-60 in 10m sections, cost £200,000
Bonus 1000: tower heights 50-70 in 10m sections, cost £300,000
Tower costs: £1000/m
Windfarm layout
5 WTGs
Minimum WTG separation: 80m
Maximum WTG separation: 500m
Use previous WTG layout as initial solution
Inter-WTG infrastructure costs: electricity network £24/m, road access £52/m
Electricity Output
Energy output: layout dependent - wind PDF and interpolated manufacturers power curve
Turbulence wake exponents: intermediate wake 1.13, far wake 1.0
Traditional Cost Maps
Electricity network: $100m^2$ resolution based on local features
Road access network: $100m^2$ resolution based on local features
Externalities (For subsequent true-cost optimisation)
Visual costing: layout dependent - linear, WTG layout as a group
Acoustic noise costing: layout dependent - average house cost of £62,000
Accident cost: energy output dependent - 0.0023p/kWh
Decommissioning cost: scrap costs repay decommissioning
Emissions: energy output dependent - inconclusive
Expert Areas
Area 1: A70 corridor including Douglas, Glespin and Uddington; medium population density some historical packages
Area 2: Open moorland with sheep grazing at elevation greater than 150m, zero population
Area 3: M74 and B7078 roads, 400kV transmission corridor, low population density
Residual: all other areas

Table 7.5: Windfarm optimisation parameters.

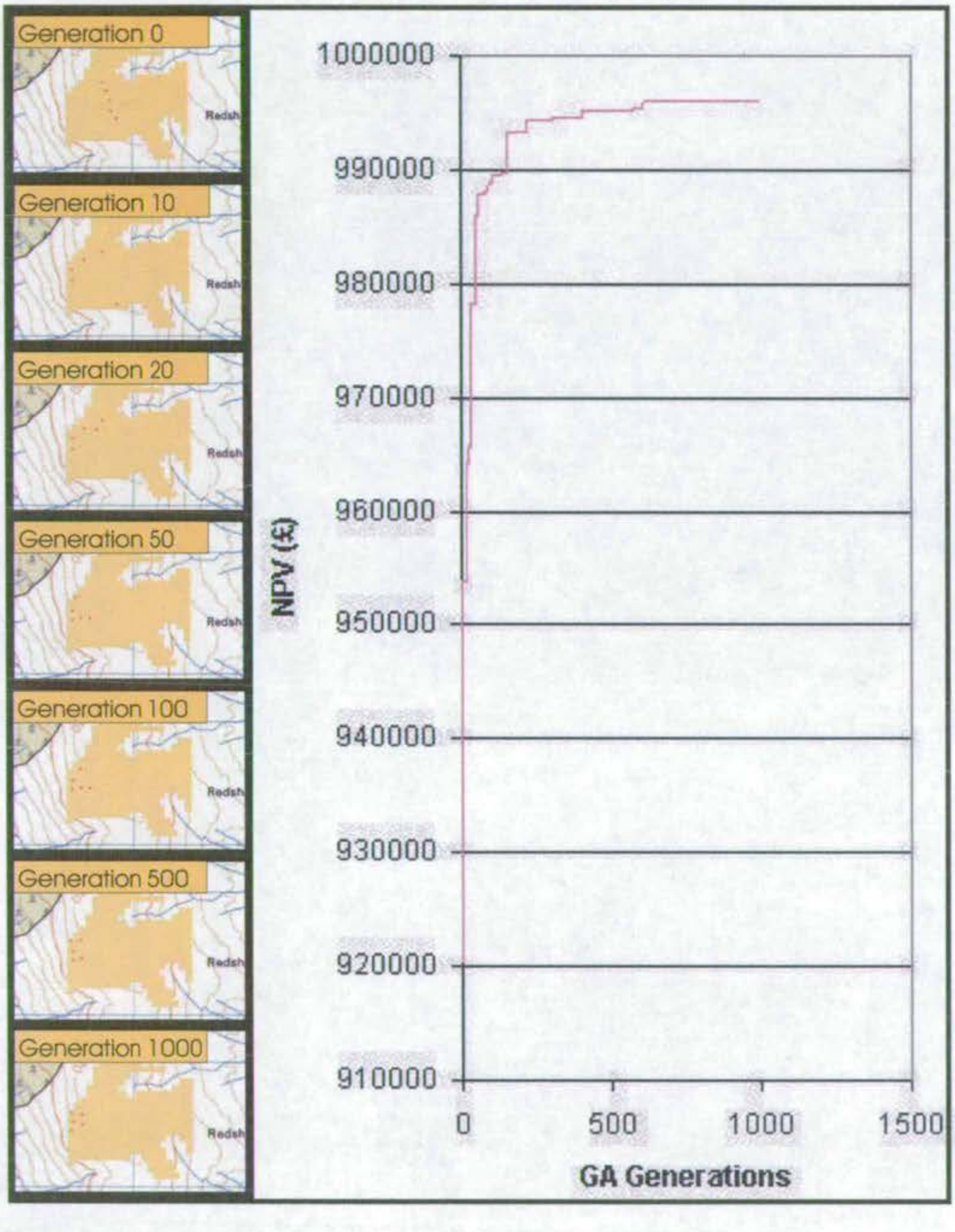

Figure 7.5: ExWind GA layout optimisation.

The external costing is carried out following the traditional costing layout optimisation to provide further project optimisation with inclusion of externalities.

7.4.4 Visual Impact Costing

Figure 7.6 refers to the ExWind returned visual impact cost map per inhabitant for the optimal traditionally costed WTG layout. The regression coefficients returned for each locally characteristic area (labelled as expert areas 1, 2 and 3) are used to produce the correct visual costings for each individual area. Those map areas outside the defined areas are referred to as the residual area.

Neither the residual area nor area 2 contain any population, therefore no regression coefficients from CV valuations are returned and the initial visual impact cost relationship (linear with distance) is returned. If this area were associated with tourists or other temporal visitors a CV or travel cost survey may be conducted by ExWind on such people to ascertain visual impact costs. No area surrounding Pagie Hill is in this category. The

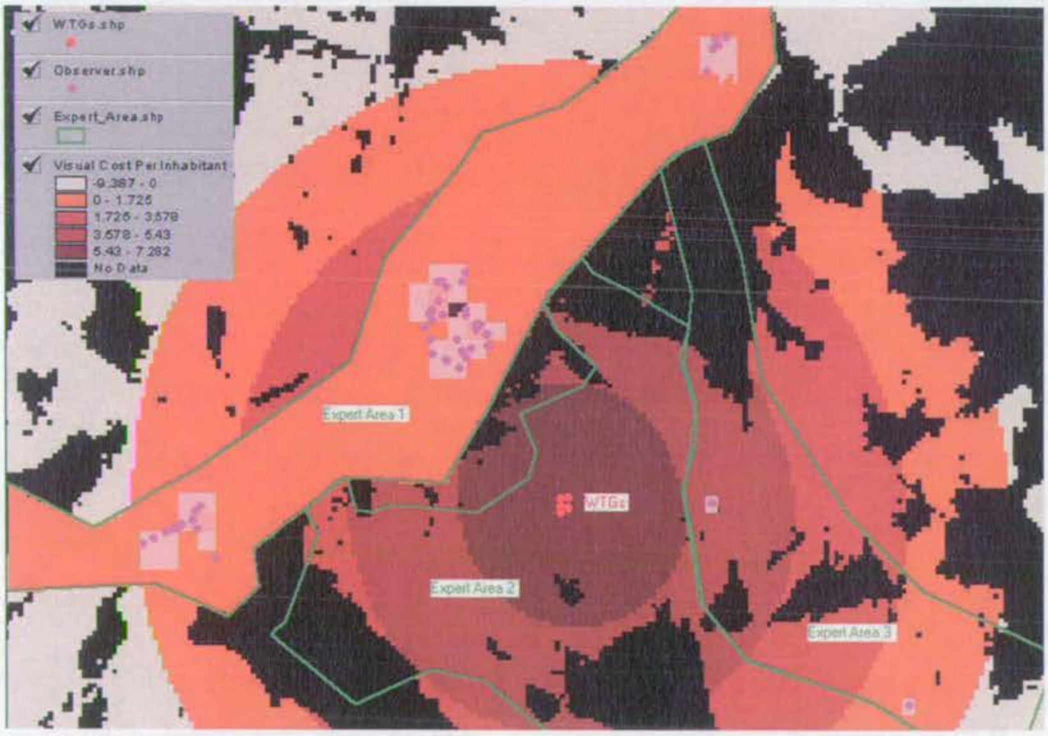

Figure 7.6: Pagie Hill windfarm: visual costings derived from CV survey.

total visual impact cost returned for the entire population affected by the proposed development on Pagie Hill is £96,990.

7.4.5 Quantification of Acoustic Noise Costs

The background noise levels were measured at the points shown (yellow points) in Figure 7.7, higher dB(A) levels being found in proximity to the B7078 or M74 roads to the east and those areas in proximity to the town of Douglas to the north west. The resulting noise level change map due to the proposed WTGs (red map points) is shown to affect no populated areas [2]. Therefore the proposed Pagie Hill windfarm creates no cost associated with acoustic noise to the locally resident population.

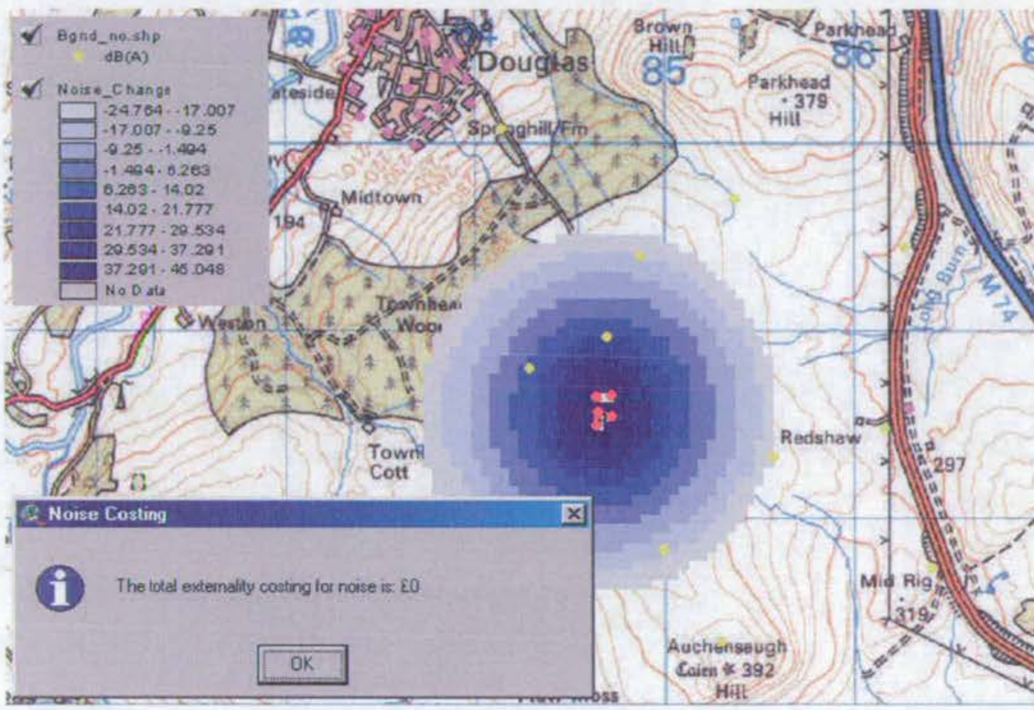

Figure 7.7: Pagie Hill windfarm: change acoustic noise.

7.4.6 Quantification of Electromagnetic Interference Costs

Figure 7.8 records the positions of the transmitters local to Pagie Hill and the EMI caused by the proposed windfarm. The local mobile phone transmitters (large orange map points) produce no conflict with the windfarm proposals, their service areas being away from the proposed development. Terrestrial television broadcast is from the Mary-Hill transmitter (Central Scotland); the likely EMI is illustrated but affects no member of the local population. No mitigatory measures are therefore required, so the resulting cost due to EMI is zero.

[2]According to the European Wind Energy Association Best Practice Guidelines for Wind Energy Development the smallest audible acoustic noise difference is 3dB(A).

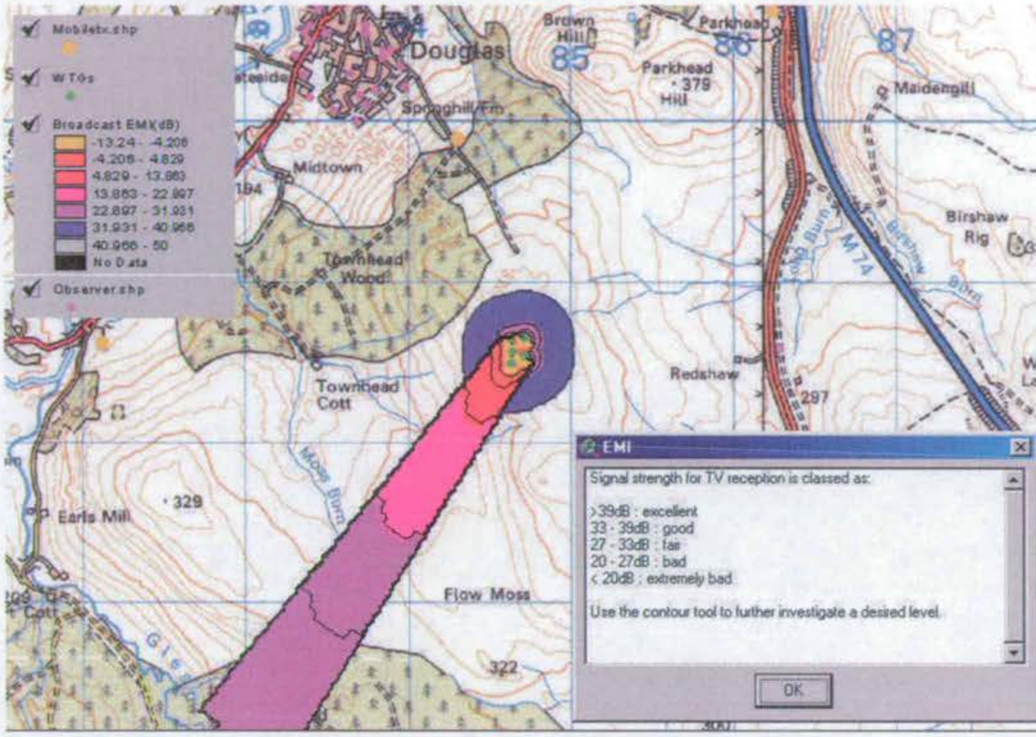

Figure 7.8: Pagie Hill windfarm: electromagnetic interference.

7.4.7 Other External Costs

Pagie Hill is not a designated area with regard to ecology or habitat. The area is best described as rough moorland suitable for limited sheep grazing. No specific ecological mitigatory measures are required.

Externalities associated with energy production (cost of accidents, emissions saved and decommissioning) are taken as the national averages (Sections 4.4 and 4.5) as no special circumstances present themselves.

7.4.8 Combining External and Traditional Costs

All external costs are defined for the proposed Pagie Hill windfarm and total £98,755, equivalent to an additional 0.04429 p/kWh. Further, relationships defining visual impact cost for the surrounding area have been identified. The common base of monetary value is now used to integrate the traditional and external costs and benefits to provide a truly optimal project.

ExWind is used to derive cost maps for each applicable external cost, each possible WTG position within the development area being evaluated according to visual impact cost, acoustic noise cost, EMI cost and shadow flicker cost. As with the initial WTG layout, no WTG position within the development area derives an external cost associated with acoustic noise, EMI or ecology. Visual impact costs are however significant at all possible WTG positions.

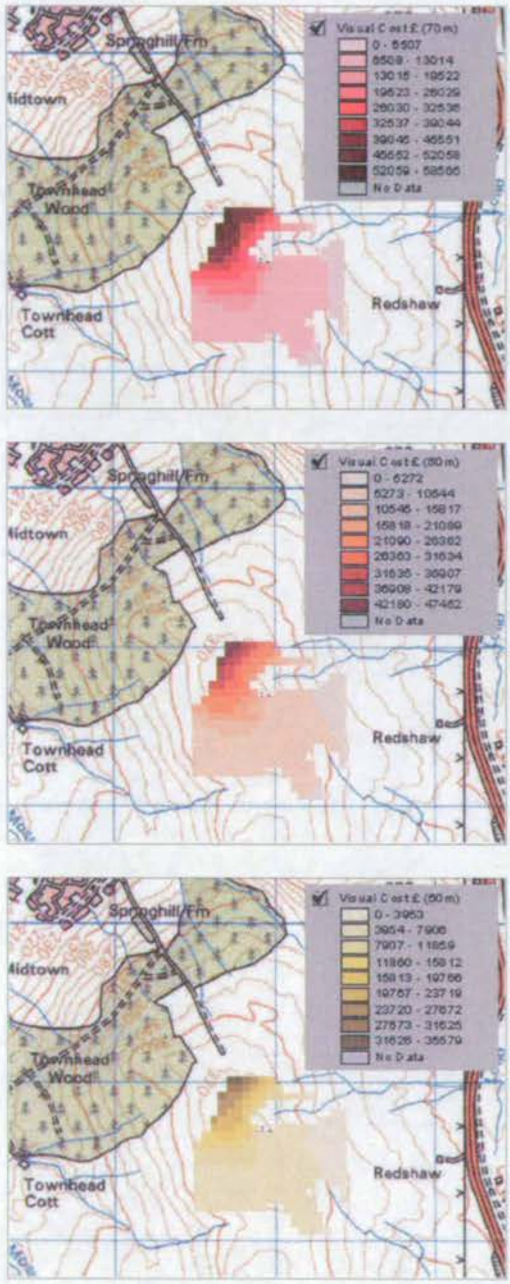

Figure 7.9: Pagie Hill windfarm: visual impact cost map (60m WTG).

Figure 7.9 illustrates three visual cost maps (WTG heights of 70m, 60m, 50m) from a series of visual cost maps for WTG heights of between 50m and 80m in 5m steps.

The external cost maps are used by the WTG layout optimisation GA along with all other relevant project costing data and the financial parameters (Table 7.6) to produce the windfarm of optimal local welfare. The financial parameters are set to reflect possible

Factor	Parameter	Error bounds(±%)
Lifetime (years)	20	-
Discount rate (%)	10	2
Energy output (kWh)	Layout dependent	5
Electricity selling price (p/kWh)	3	5
WTG availability (%)	90	3
Visual cost (£)	Layout dependent	15
Noise cost (£)	Layout dependent	5
Accident cost (£)	Layout dependent	2
Ecology cost (£)	Layout dependent	5
EMI cost (£)	Layout dependent	2
LCA cost (£)	Layout dependent	2

Table 7.6: Financial parameters for example analyses optimisation.

project conditions. The project lifetime, WTG availability, and electricity selling price mirror current conditions. The discount rate is cautious while the externality valuation error bounds are estimates prior to a large volume of such studies being carried out. All financial parameters are editable, the associated effects of a change being immediately apparent in the returned ExWind financial appraisal.

The optimised windfarm layout is presented in Figure 7.10. The WTG layout is noted

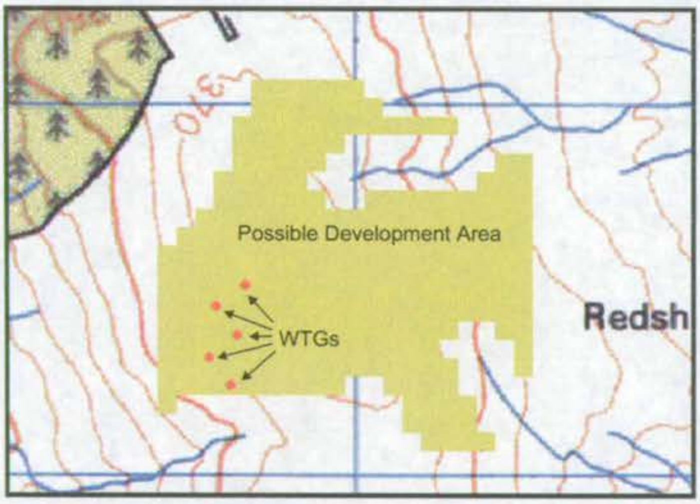

Figure 7.10: Pagie Hill windfarm: optimum layout.

to be of a regular pattern as specified by ExWind according to the local landscape characteristics, the inter WTG distances (97m) optimised to provide greatest energy capture against cabling and access costs. The WTG array faces the most probable wind direction for maximum energy capture. The windfarm position makes use of the higher windspeeds and lower visual impact costs traded off against the higher road access and electricity connection costs associated with the south-west corner of the development area. The optimium WTG for the wind regime is a Bonus 600kW machine, the optimum WTG height, derived as a tradeoff between energy capture and visual impact, is 60m.

The financial results of this project are displayed in Figure 7.11. It may thus be con-

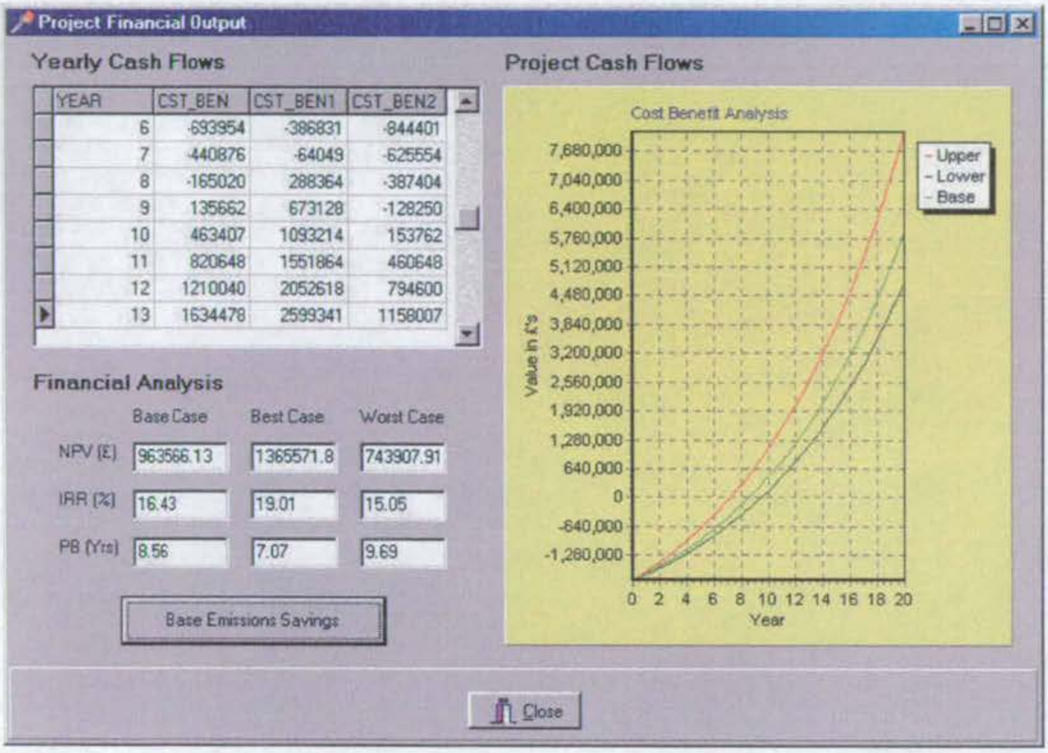

Figure 7.11: Pagie Hill windfarm: true costing financial results.

cluded that the Pagie Hill windfarm is profitable by true-costing methods and should be accepted as a viable proposition.

7.4.9 Local Verification of True-Cost Optimised Windfarm

The ExWind optimised windfarm layout is used as the basis for a further examination of the locally derived externalities in order to assess if the returned windfarm layout is an improvement over previous versions with regard to externalities. The population sample used in the original CV survey and 32 new respondents were asked to provide either new contingent valuations concerning the impacts or in a basic test of design improvement, to decide which windfarm they preferred between the initial traditionally optimised layout and the true cost optimised layout. The results are summarised in Table 7.7. The optimised windfarm layout improves over the initial traditionally costed layout in external monetary terms (original visual impact of £96,990 compared to optimised of £41,509). This result is endorsed by the majority of those interviewed (77.4%) for whom the new windfarm layout is an improvement.

Study	Results	
Contingent Valuation	Initial layout valuation	£96,990
	Optimised layout valuation	£41,509
General Questionnaire	Prefer original layout	12.7 %
	Prefer new layout	77.4 %
	No opinion	9.9 %

Table 7.7: Verification of ExWind visual impact optimisation.

The actual visual cost (£41,509) of the new windfarm is lower than that anticipated from ExWinds visual impact costing (£43,584), by approximately 5%. It would seem that this is a small overestimatory error to be included in the final financial analysis error bounds. The error may result from the relatively small population surveyed in the pre- and post-optimisation studies not returning a completely true representation of the spread of valuations. Evaluating all valuations against actual observer position with respect to the windfarm, it is observed that the reduction in visual impact cost is directly related to the number of observers for whom the windfarm is visible.

7.5 Discussion of Issues Arising in ExWind

The relevant algorithms produced to provide costings (both external and traditional) are verified in Section 7.2. All wind velocity calculations, WTG electrical energy output and financial algorithms are based on well documented work and are in agreement with test analyses. However, specific areas of uncertainty wholly incomparable with previous work do however exist and must be carefully examined regarding the analyses results.

7.5.1 Externality Quantification

The use of a monetary base for the combination and optimisation of external and traditional cost-benefit elements associated with an electricity generation project produces realistic and profitable windfarms, as proven by the ExWind ouput and subsequent verification of the results using CV and survey techniques. The accuracy of the external costing methodology, although producing an overestimatory error of 5%, does return a significantly more acceptable windfarm than the traditional costing alternative for an NPV disbenefit of £32,523 (£996,089 minus £963,566). However, this loss in revenue is compensated for in the true-cost analysis by reduction of the external costs between projects, and crucially, the increased chance of project planning approval.

If the monetary quantification of externalities proves unacceptable in any given circumstance, ExWind can revert to simple external impact indices despite their incompatibility with traditional costs. Rather than deriving externality associated cost maps, 'cost maps' defining the impact indices can be used in project optimisation.

7.5.2 Layout Optimisation

The GA optimisation characteristic (Figures 7.5 and 7.12) is highly dependent on the cost maps employed and WTG layout desired. For example, the traditional cost maps create a fairly continuous cost function and hence solution space for the GA. Thus the solution fitness becomes greater fairly consistently in the expected exponential manner (due to fewer better solutions being available for later generations) unless mutation or crossover produce significantly better results (a step). Figure 7.5 corresponds to such a convergence.

The complete costing introduces additional complexity as the traditional cost maps are in tension with the external cost maps and the constrained WTG layout (if desired). The choice of a regular WTG layout limits the possible layout permutations as all WTGs must fit into the development area. Any ExWind solution where part of a regular layout (*i.e.* one or more WTGs) is outwith the development area thus contributes no benefit to the project and an extremely low NPV is returned. This leads to a much more binary search space of very good or very bad solutions, resulting in good solutions being kept longer (due to the difficulty in breeding good new chromosomes even though the overall population fitness is increasing) until eventually a better layout is found. Figure 7.12 illustrates such a radically stepped characteristic.

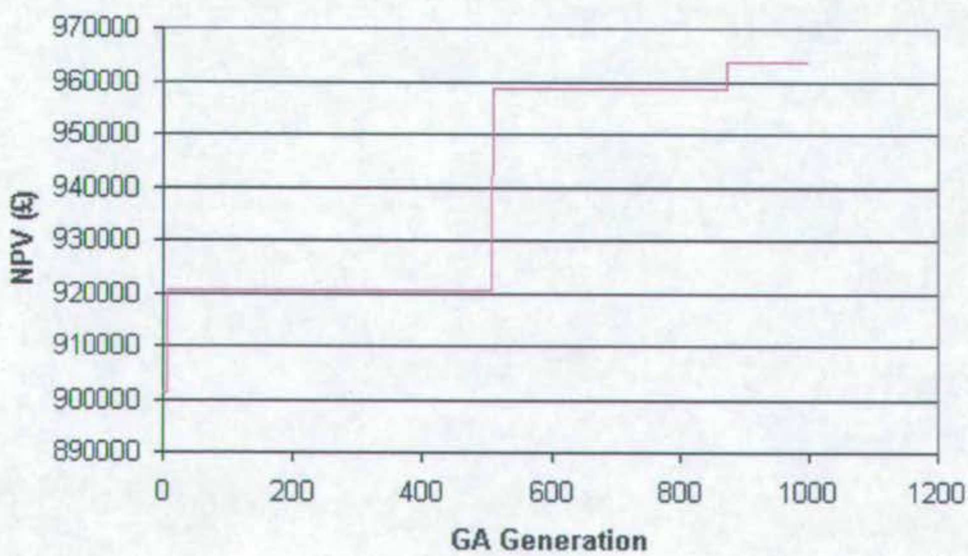

Figure 7.12: GA convergence for the regular true-cost WTG layout.

GA optimisation of the windfarm layout was tested for a number of heuristic starting points to determine sensitivity to the initial conditions. The final results (Table 7.8) confirm a high degree of convergence to the optimal solution independent of the initial conditions. Although GA convergence is independent of the initial conditions, the drift between generations to a solution is longer unless a beneficial mutation occurs. The layout and GA parameters used are those recorded in Table 7.5. The average WTG positional error is the average distance of a WTG in a layout solution from the corresponding WTG in the best solution as judged by NPV.

Run	NPV (£)	WTG positional error (m)
1	963,566	0.0
2	963,536	3.8
3	963,145	3.4
4	962,897	5.6
5	962,760	7.2
6	962,489	12.0
7	962,176	6.1
8	960,833	16.7
9	960,831	19.9
10	959,983	22.4

Table 7.8: Genetic Algorithm WTG layout convergence.

NPV over a 20 year project lifetime is very sensitive to small changes in the initial siting conditions. The NPV error bounds observed (£963,566 to £959,983 or 0.37 % of the final NPV) are therefore acceptable. A greater gene population or a larger number of generations would yield better results at the expense of longer processing times. As expected by the sensitivity of the NPV measure, layouts prove to be very similar. Only with a duality (or more) of optimum values would a number of equally good but different solutions emerge, a situation unlikely with regard to a windfarm containing a large number of cost constraints.

7.5.3 Visualisation of Windfarm

A number of issues emerge regarding windfarm visualisation.

1. Insufficient screen resolution for high quality renderings.
   The photomontage quality is severely degraded at the normal screen resolution provided by a PC. Therefore photographic quality photomontage (ExWind derived) print-outs were used rather than an on-screen picture. These high resolution pictures take longer than a standard picture to process.

2. Panoramic scene composition.
   The digital camera allows the joining of adjacent photographic frames to produce a panoramic view of the proposed development site, clarifying the possible visual impact.

3. Perceived vertical picture compression.
   A digital camera suffers less from vertical compression than a standard camera (ratio 1.487:1.333). This produces a more realistic impact representation when

viewed at the correct viewing distance to allow for scaling effects, for example 23cm for a standard 6 inches by 4 inches photographic print [197].

7.5.4 Contingent Valuation

Despite the novelty of responding with a monetary value for a resource not normally valued in this manner (i.e. visual amenity), the population sample made few comments as to the unacceptability of such a practice. A number of reasons may exist for such a positive response.

1. The CV questions were clearly framed within a realistic cost situation of which the participant was aware (added cost to respondent electricity bill for the increased cost of non-locally produced electricity if the existing windfarm were to be removed or the proposed windfarm to be rejected). This mechanism, although desirable for true-costing approaches, does not currently exist. However, in a properly liberalised market the location of generation plant and consumer would play a role in price determination. The respondents to the CV survey seemed to recognise this factor when questioned even though it is not a currently implemented measure.

2. The increase in bidding style auctions in the media or on the Internet is increasing widespread acceptance of WTP for a commodity.

The local population cannot know the full cost or benefit of a windfarm as too many factors beyond their knowledge and expertise exist, but, their valuation of the impacts applicable to them is valid. It was therefore stressed that normal financial considerations decided if a particular windfarm performed its function viably or not, therefore only those impacts affecting the individual were being costed. Separation of visual impacts from all others (the avoidance of embedding) was not a significant problem. The sample population was asked to identify which externalities would directly affect them, the majority quoting only visual impact. Only one protest bid was recorded from a respondent who openly admitted to be doing so.

The response to the computer aided questionnaire was less positive. Initial comments concerning the distrust associated with technology and the difficulty in checking that the interviewer was recording the correct answers led to the questions being printed out in paper form. This had already been carried out to produce visualisations of an acceptable quality. The survey then took place as a normal paper, pen and showcard exercise.

7.6 Summary and Discussion of Resulting Externalities

The results returned by a local population through ExWind are notably different depending on whether externalities are evaluated for an existing or planned windfarm.

7.6.1 Study Results and Comparisons

The final externality valuations (specific to the sites in question) are summarised along with the general ExternE results in Table 7.9 [3] [4]. The results from the chosen studies

Externality	Hagshaw Hill (Existing)	Pagie Hill (Planned)	ExternE [198] (General)
Visual impact	0.84	44.29	NQ
Noise impact	0	0	0.04 - 0.67
Ecology impact	0	0	-
EMI impact	0	0	-
Accidents	0.21 - 2.3	0.21 - 2.3	0.21
Emissions	0.51	0.51	0.51
Decommissioning	0	0	-
Total	1.56 - 3.65	45.01 - 47.10	0.76 - 1.39

Table 7.9: Summary of windfarm externalities in $\times 10^{-3}\mathrm{p/kWh}$.

indicate significantly higher external costs than previous studies (ExternE), primarily due to the addition of visual impact costs. Despite using exactly the same methodology (WTP) for both the existing and proposed studies the visual impact costs are approximately fifty times greater for the proposed windfarm. This is a significant result discussed below. The visual costings for the proposed windfarm (≈ 0.04p/kWh) are significant in the context of financial optimisation; however, they should prove a surmountable obstacle regarding local project success.

7.6.2 Examination of Externality Quantification

The disparity between WTP concerning the visual impact of an existing windfarm and that for a proposed windfarm is not inconsistent with the theory of external costing at a local level. Sociologically, the examination of two differing proposals to which differing attitudes and circumstances are attached should yield disparate responses.

It is notable that very few of those surveyed wished to pay to remove the windfarm as compared to the valuations derived from suggestions of a new windfarm, even though both studies concentrate on a similar area. General question responses revealed no significant preferences against further windfarm development in the locality. These findings may indicate that visual impact is a perceived pre-development problem. The dialogue and effort to mitigate a development plan is therefore most useful pre-project in order to gain project acceptance.

The results suggest that hindcasting yields little helpful data in deriving monetary values for a proposed windfarm, due to the seemingly irrational/inconsistent responses pre- and

[3] Hagshaw Hill electrical output is estimated as 63,073MWh per annum, Pagie Hill output as 10,970MWh per annum for a 20 year WTG lifetime.

[4] Emissions cost does not include the benefits of offset emissions.

post-development for those who have experience of windfarms. The actual external cost of a windfarm may be very low after construction, although this in no way negates the relevance of quantifying pre-project external costs, which are, at the very least, crucial in project acceptance and implementation. A wholly imagined or fictional cost may still lead to project rejection, a scenario the international financial markets are well used to.

As experience of windfarms increases and the gap between perceived and actual benefits or disbenefits decreases, the initial pre-development costings may decrease. It is, however, notable that even in the area studied where there is experience with a windfarm, the cost associated with an additional windfarm nearby is still considerably higher than that for the existing windfarm. This may reflect the uncertainty associated with the impacts of a new development and the human predisposition towards the status quo.

7.6.3 The Local Nature of Results

Although externalities have been quantified for the windfarms in question, these results are not specifically transferable to any other windfarm, proposed or existing, due to the specific geographic information contained in each study. The two analyses at Hagshaw Hill and Pagie Hill are within a similar area allowing general comparisons to be drawn. It is, however, more important that the results do appear to be consistent at a local level as argued throughout this thesis.

The general lessons are noteworthy with regard to general public attitudes pre- and post-windfarm development, and the use of the specific methodology contained in this thesis. The results should form the basis of guidelines for future windfarm development.

7.7 Summary

The algorithms evaluating traditional and external costings have been tested and are found to return logical results in agreement with previous windfarm designs, or significantly improving on manually designed projects.

ExWind methodology is capable of determining profitable sites and optimal windfarm layouts through use of the initial site profitability filter and GA layout solver respectively.

The externalities associated with any particular wind project may be identified, quantified and traded off against traditional costings.

There is a marked difference between the externalities associated with an existing windfarm and those associated with a proposed windfarm. As predevelopment externality valuations may represent valid opinions which will affect the success of the planning process the pre-project valuations should be used in the initial site design.

The dependence of cost on the distance of the consumer from the generator is recognised by the population sample in this survey. Inclusion of this cost as a part of true-costing may go some way to solving acceptance of dispersed RE projects at a local level in the form of lower electricity bills - a direct benefit to those affected.

The example studies show an added project cost (in developer terms) of £32,523 over the initial traditionally costed windfarm when externalities are included in the windfarm design. This cost should be reflected upon with regard to the costs incurred by a failed proposal. Assuming that the inclusion of local dialogue to evaluate externalities produces a more locally acceptable project of lower external cost (as the Pagie Hill study would suggest), the likelihood of project success is increased and thus the methodology is valid and should be used.

Welfare distribution has been optimised for a particular wind project, all relevant costs and benefits are accounted for.

Chapter 8

Conclusions

This chapter concludes the thesis with a summary of the key arguments and findings. Recommendations for future work are outlined and general conclusions drawn. The principle objectives of this study are summarised as:

- The examination of externalities in the UK Electricity Supply Industry (ESI) and the implications (by their inclusion or omission), as regards national energy policy and future generation choice.
- The development of a methodology quantifying specific externalities in monetary terms.
- The use of externalities, quantified in monetary form, as a part of project cost-benefit analysis and welfare optimisation.
- The development of a GIS and GA based windfarm design optimisation tool.

8.1 The Implications of Externalities

Optimal welfare distribution provides an efficient (least cost) use of resources accounting for all factors and timescales. In liberalised markets, it is the market mechanism itself which attempts to create this ideal, the efficiency of optimal resource allocation often being claimed as the foremost reason for undertaking such reform. However, it has been shown that where externalities exist a market mechanism will produce inefficient and sub-optimal resource allocation.

8.1.1 Externalities in the Generation of Electricity

The significant unaccounted costs and benefits, termed externalities, existing within the UK ESI have been identified. The drivers for the inclusion of externalities have gained acceptance with the realisation that previously unconsidered effects produce environmental and social costs not included in the market price of electricity, for example, the emissions associated with electricity generation from fossil-fuelled plant. Good agreement on the appropriate quantification of externalities or the measures required to include these factors within least cost planning (LCP) does not presently exist. The inclusion of externalities in LCP is shown to have a significant effect on the choice of electricity generation methods, particularly in the case of renewable energy (RE). Scenarios including externalities predict a decline in fossil fuel electricity generation and a much greater penetration of RE technologies.

Various mechanisms have been examined which attempt to include externalities and thereby encourage a more optimal allocation of resources. Price based mechanisms such as fuel taxes, quantity based mechanisms such as tradeable emissions permits, and market stimulation measures such as fossil fuel levies or green tariffs have been implemented with varying degrees of success.

8.1.1.1 Shortcomings of Current Compensatory Mechanisms

It is noted that each currently implemented mechanism requires a decision as to where the equilibrium point between marginal cost and benefit (the optimal level of global welfare) should lie. This is undertaken in a qualitative manner as few attempts quantifying specific externalities to a monetary base that is measurable against traditional costing methods have been implemented.

This thesis suggests that it is possible to ascribe a monetary valuation to externalities by use of a bottom up impact pathway together with the careful application of economic techniques determining traditional and external cost-benefit quantification.

8.1.2 The UK: National Implications

The UK ESI has long been subject to command and control regulations accounting for some externalities (primarily the upper levels of harmful pollutants) associated with electricity generation. The move to a liberalised market has led to a move towards price based mechanisms (Climate Change Levy) and market stimulation measures (Fossil Fuel Obligations). The introduction of such measures is noted to have required additional legislation and regulation. There have been claims of inefficiency, particularly with regard to the Fossil Fuel Obligation in direct comparison to other European schemes.

The UK Government's energy policy is based on promoting security, diversity, sustainability and competition in electricity supply through the Regulator OFGEM. The specific point of responsibility concerning implementation of energy policy is observed to be unclear, resulting in levels of achievement significantly lower than governmental targets. Currently there is little incentive for longer term or perceptually risky investment even when directly in line with the tenets of government energy policy. Prime examples of this are the commitment to produce 10% of UK electricity from renewable resources by 2010 (sustainability and diversity) and the lack of interest in the projected decline of the nuclear power industry (security and diversity).

NETA and the forthcoming British Energy Trading and Transmission Arrangements (BETTA) currently exhibit no provision for the mitigation of such problems, nor do they account for the inclusion of externalities. The inclusion of externalities is likely to be derived from a blanket fossil-fuel Climate Change Levy applicable equally, for example, to CCGT and to coal fired power stations despite their emissions differences. It is thus concluded that within the UK there is no consistent policy or long term strategy evident for the quantification or inclusion of externalities. This is likely to lead to sub-optimal welfare distribution and the failure of basic governmental energy objectives.

8.1.3 Local Implications

Externalities at a national level are ultimately the aggregated externalities derived at local levels. Locally derived externalities should therefore be measured for eventual comparison at national and ultimately international levels to produce optimal welfare globally. The advent of cheap, reliable and powerful computing, with access to readily available data, brings closer the realisation of this goal at a national level, but global optimisation is unlikely in the foreseeable future. Local quantification of externalities from which national and perhaps, eventually, global optimisation studies are formed is therefore implemented in this work.

It is observed from the study of planning applications that the externalities at a local level may however be more significant than those at the aggregated and averaged national level. This is due to generation siting being a local factor. Aside from significant local externalities contravening the principle for optimal welfare distribution, certain sectors of the ESI have also discovered that such locally perceived externalities for a proposed project can lead to project abandonment at the planning stage.

8.1.3.1 Projects in the National Interest

In the past government policy based on the recognition of traditional and external cost-benefit analysis pushed through generation plans at a local level that were in the national interest. However, in the liberalised market, financially sound electricity generation plans meeting government policy criteria but incurring a certain amount of external cost locally may not resort to promotion for the sake of the national interest despite the possible external benefits at that level. This applies particularly to dispersed generation technologies such as renewables, and has led to the rejection of profitable schemes due to a vociferous minority who justifiably claim to incur local costs. However, the incurred local costs may however be insignificant as compared to the national benefit. Thus the move to a liberalised electricity market often takes less account of externalities than the nationalised system of old.

8.1.3.2 Successful Local Development

It is argued that the quantification of the specific monetary external costs and benefits of an electricity generation project at a local level provides the desirable developer with the means to optimise that project according to local welfare. This is likely to increase the chances of successful project development, particularly during applications to the planning authorities. The comparison of the locally quantified costs and benefits with similar projects allows selection of that project most suitable by true-costing methods.

8.2 Quantification and Optimisation of Externalities

Traditionally, index based systems have been used to quantify external impacts and these are subsequently offset against the desired project outcomes. The cross-comparison of monetary and index based measures is prone to error and miscalculation, therefore it is suggested that quantification to a common monetary base is by the economic methods of contingent valuation (CV), hedonic pricing, travel cost and dose response functions. Although none of these methods may claim complete accuracy, the level of error associated with impact quantification is conceptually no more than that derived from index based studies and in reality considerably less due to its local derivation. It has been proven that a carefully undertaken CV study is particularly applicable when quantifying the external impacts on a local population, the results from ExWind remaining consistent for various windfarm layouts and population samples at a single site. The quantitative results broadly match the qualitative index style responses for each project studied, inferring that monetary quantification provides information which is at the very least consistent with other forms of impact assessment, but with the added advantage of being readily comparable to traditional monetary cost-benefit methodology.

8.2.1 Wind Generation and Externalities

Observations of recent planning applications to build generation plant in the UK show a high rate of project failure due to unaccounted externalities [199]. Wind power developments are noted to be particularly prone to this type of failure. A methodology to quantify the externalities associated with electricity generation from windfarms has been successfully developed and applied to a number of relevant case studies within Scotland. These studies are the first aimed at specific local quantification of externalities without generalisation or extrapolation of results as the primary aim.

8.2.1.1 ExWind

The requirement to use a bottom up impact pathway approach to evaluate locally derived externalities suggests a large data requirement and the use of a geographic reference system. A geographical information system (GIS) is utilised for the efficient storage, manipulation and output of the geographically referenced data. The software implementation of the developed methodology, ExWind, is an extension to ArcView GIS. The GIS has proved an adaptable, intuitive and reliable basis for this task, additional functionality being integrated through external functions written in a standard programming environment. Although complex, transparency is retained in ExWind evaluations by the high degree of data representable in intuitive map form and a suite of graphical user interface (GUI) driven functions providing query and analysis options. The data required (wind turbine generator (WTG) details from the manufacturer and local geographic characteristics from the OS) is readily available in electronic form, which is stored in ExWind upon conversion to the correct format. All project parameters are user editable to reflect local circumstances, project redesign and future circumstances.

The software has been verified to produce good solutions to the layout of the WTGs according to all relevant parameters: wind velocity and its variance with local features, WTG electrical energy output, WTG characteristics, accurate infrastructure routing and the quantification of externalities (visual, acoustic noise, ecology, electromagnetic interference, accidents, decommissioning, life cycle analysis). All costs and benefits associated with the aforementioned parameters may be optimised for a particular windfarm to produce the optimum project at that locality.

8.2.1.2 Efficient Windfarm Optimisation

The optimisation of the three dimensions of a real windfarm development, the infinite number of WTG positions, varying WTG characteristics, WTG interaction, WTG number and the existence of both external and traditional cost functions present enormous complexity compared to that entailed in a straightforward cost-benefit analysis.

Exhaustive optimal solution search techniques do not efficiently solve such problems and artificially intelligent techniques have been adopted. The optimisation of a large number of dependent and non-linear parameters defining the structure of a windfarm is efficiently carried out by a number of genetic algorithms. The optimised results are accurate and consistent, accounting for all relevant project details. GA convergence to an optimum is independent of the initial heuristic or random solution applied, more efficient solutions being derived by the use of previous satisfactory windfarm layouts. The convergence characteristic varies from an exponential form to a very stepped response dependent on the type of costing and layout required.

8.3 Lessons from Research

The results prove that it is possible not only to quantify externalities in monetary terms but also to use these values to optimise local welfare against project profit. The resultant WTG layout provides a project of acceptable or reduced external cost which remains profitable by traditional costing methods. However, there are however a number of specific observations of note.

8.3.1 Discrepancies in Externality Quantification

Impact valuation discrepancies result between existing and proposed projects. The valuations within each of these project types is, however, consistent, the differences being attributable to social perceptions. These perceptions may change as public experience of the realities of windfarm impact increases acceptance.

8.3.2 Lessons for Proposed Windfarms

Without careful regard to externalities the success rate of windfarms and indeed other dispersed RE technologies will continue to decline. Even though the pre-development external cost of a windfarm is likely to be much greater than that some time after implementation, it is the initial externalities that determine planning success. Their quantification and mitigation is therefore of paramount importance.

8.3.2.1 Local Compensation for Impacts

General benefit is currently lacking on a personal level for those impacted or incurring perceived costs from a windfarm, thus decreasing willingness to accept such development. Mitigation of such issues may be possible by the introduction of mechanisms beneficial to those so affected. The studies undertaken were concerned with eliciting the monetary value of externalities rather than a compensation mechanism. They therefore used the respondents monthly payment for electricity as the entity upon which the willingness to pay for removal of an impact was based. This mechanism provided consistent monetary values although other mechanisms providing a transparent payment mechanism for impact compensation may also be appropriate. The likely mechanisms might include:

- a reduced electricity bill in recognition of the advantages of locally produced electricity,
- the possibility of participation in Danish style co-operatives where local people are entitled to part ownership of the windfarm [1],

[1] The use of Green Credits in the UK to allow suppliers in urban areas to meet their RE obligations under

- a cash payment (one-off or spread over time) to those affected.

The final local external cost from a windfarm of $\approx 0.04\text{p/kWh}$ is of little significance as compared to the traditional project costs. A developer is therefore likely to view such compensation as a small price to pay for a successful windfarm. If contingent valuation were commonly used, strategic bidding (associated with the public realisation that there were self-set benefits to be had) would be an increasing problem unless there were equally likely disbenefits from the windfarm not being built. It is therefore likely that the locally derived cost or benefit will recognise the monetary value of local electricity production or the external costs associated with a population elsewhere who are willing to allow the siting of a generator.

There is currently no evidence to suggest that visitors to an area or through-travellers derive any significant disbenefit from windfarms. With the projected increase in the number of windfarms this may change thus requiring mechanisms for appropriate compensation.

8.3.2.2 The Significance of Visual Impact

The externalities associated with a normal windfarm site more than 500m from habitation in a non tourist area are dominated by the visual impact cost. This previously unquantified cost appears to create the largest barrier to windfarm development. Developers do not yet include specific in-depth visibility calculations as an initial parameter when optimising initial site selection, but rather post site selection as a zone of visual impact (ZVI). This thesis proves that visibility analysis is a critical parameter in site selection, the visual impact costing being directly proportional to the number of people for whom the windfarm is visible and the intervening distance.

8.3.3 General Lessons for the ESI

It has been proven that even highly subjective criteria deriving externalities may be quantified in monetary form with some certainty, for example, visual impact . It is therefore surmised that application of these techniques to other electricity generation methods is likely to be successful and useful in determining true LCP.

A major hurdle requiring intense research effort is that of determining or estimating the true costs of emissions from fossil-fuelled electricity generation for a specific locality. Although the impact pathway methodology embodied in a GIS is suitable for such studies, data requirements are likely to be extreme.

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the new Utilities Bill may encourage a market for the involvement of rural communities in RE projects.

8.4 Recommendations for Future Work

The work in this thesis, although complete in itself, has a number of possible avenues for expansion which the limited period of study did not allow.

8.4.1 Expansion of ExWind Studies

Similar analyses to those undertaken for Hagshaw Hill and Pagie Hill should be carried out for a large number of additional sites. Although resource intensive to implement, a large body of results would further reveal trends in the externalities associated with windfarms. This would greatly aid future planning applications, particularly with regard to the true post development cost of a windfarm to a local population.

8.4.2 Evaluation of ExWind for a Real Windfarm Development

During initial evaluation of the externality quantification and optimisation methodology it was deemed unsuitable to be involved with a real windfarm proposal. This was because the effects of using a methodology involving local participation were unknown, any bias produced causing possible financial loss to the developer.

The methodology has now been proven and could provide valuable planning advice to a windfarm developer, not least in producing local planning approval. Therefore evaluation of ExWind within the context of a serious windfarm proposal should be implemented.

8.4.3 Advanced Visualisation Techniques

The static photomontage visualisation could be improved by the use of dynamic techniques. For example, a digital video camera utilised to provide a high resolution dynamic representation of a local landscape on which a dynamic computer generated windfarm is superimposed in real time. The ability to mount such a system on a virtual reality (VR) headset sensing the direction of the viewers head would allow the user visualisation at any part of the landscape desired, the VR windfarm always being computer rendered at the correct location. At present the resources to produce such visualisations are prohibitively expensive and unsuitable for use in the field. This is likely to change in the near future as the technology advances, although public reaction to such technology should be carefully examined.

8.4.4 National Visibility Mapping

Based on the findings of this thesis it is conceptually possible to produce a national map of estimated visual impact cost. As this has proven to be the most significant (external) cost as regards windfarm development, such a map could be used at a national level in conjunction with wind velocity maps, road access and suitable electricity network maps to redefine the likely profitable resource in a similar manner to the basic site filtering methodology utilised within ExWind. The computation power required would be large, but possibly less costly than a large number of failed planning applications.

8.4.5 Improved Electricity Reinforcement Costing

At present the model incorporates a simple electricity network upgrade cost for each existing element of the network in the area surrounding the windfarm derived from the local system operator. This allows the electricity network cost mapping to take place for all points within the area. Further work towards defining the technical constraints and therefore specific cost to reinforce these lines could be undertaken and included as added ExWind functionality.

8.4.6 Market Model

Simple but standard financial parameters are used within ExWind to evaluate project cost-benefit. For example, the price paid to the windfarm operator for electricity produced (per kWh) is set for the project lifetime. This is consistent with existing renewables orders where the price set for electricity is retained for a number of years.

In future the price paid for electricity from a WTG is likely to fluctuate according to the final implementation of BETTA and any provisions set in place to provide a market for the generation of electricity from renewables. At present many of the specific details are unclear, however, in future a market model deriving the likely monetary benefit from a time varying electricity supply is an attractive extension to ExWind.

It is not unlikely that renewables will only present an attractive investment through some form of fixed contract during the initial payback period, the market model being applicable in the later years of operation.

8.4.7 Financial Risk Analysis

In light of the possible penalties for non-compliance with contracted supply under BETTA a stochastic examination of any cost-benefit analysis accounting for the likely variations in electricity output is recommended.

The risk associated with WTG electricity output may be determined by Monte Carlo analysis to return a sensitivity analysis defining the probability of effects derived from likely changes in project variables. As the ExWind methodology returns all project variables in a transparent manner this would be easily achievable in the short term.

8.4.8 Application of Methodology to Other Generation Methods

It has been proven that it is possible to quantify externalities with some degree of accuracy at a local level for a specific wind project and thus provide optimal site design.

The impact pathway methodology is also applicable to any other form of electricity generation, although adaption to the peculiarities of any given generation cycle would be necessary. This should be carried out for further generation methods, enabling the direct comparison of various types of generating plant within a given locality or localities.

8.5 General Conclusions

This thesis initially set out to explore externalities and their impacts on the UK ESI. In order to undertake true least cost planning the UK ESI must take account of the externalities associated with electricity generation. Inclusion of externalities in LCP is likely to result in a significantly different generation mix than that currently projected, with a larger emphasis on RE. There are difficulties in quantifying externalities in a monetary form, however, a set of impact pathway techniques have been successfully implemented with regard to determining and optimising the true costs of electricity generation from wind power. The locally based geographic methodology implemented in the GIS based software package, ExWind, produces rapid externality quantification and optimisation. The methodology is applicable to other UK electricity generation methods.

The externalities quantified in monetary terms with regard to a windfarm are visual impact, acoustic noise impact, ecological impact, electromagnetic interference, public and occupational accidents, decommissioning and emissions. Visual impact of a windfarm is quantified in monetary form for the first time and found to be a critical factor in project success. By the use of evolutionary techniques it is also possible to optimise externalities in monetary form with traditional cost factors, thus producing the project of optimal local welfare. The optimisation of projects to be acceptable for both the local community and the developer should enable the penetration of windpower (and indeed other generation plant) to the level where true marginal costs equal the true marginal benefits as desired in LCP.

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Appendix A

Example Questionnaires and Visualisations

This Appendix contains the information and questions used to provide the general qualitative responses to windfarms and also those used in the contingent valuation concerning visual impact. Example visualisations are presented.

A.1 General Questionnaire

The general questionnaire was used to ascertain local views on existing and proposed windfarms. This was to provide identification of the principle external components and to provide a qualitative basis to enable comparisons with the later monetary quantifications of externalities.

Introduction

Good morning/afternoon/evening, I'm calling with you on behalf of Edinburgh University. We are interested in what people who live near to windfarms think of them. (Select person over 18 at next birthday.) Would you mind taking around 10 minutes to answer some questions? All answers will be anonymous and strictly confidential.

Sample Characteristics

1) Is this your main residence?

2) Do you own this property?

3) How long have you lived at this property?

Background and Scene Setting

We all expect a reliable and economic supply of electricity to meet our everyday energy needs. The production of electricity is normally from nuclear or fossil fuels (such as coal, oil and gas) which produce pollution or hazardous wastes. The pollution from fossil fuels contributes to climate change and global warming. It is recognised as one of the greatest threats facing our environment.

Scotland is blessed with an abundance of wind. Renewable energy projects (those using a fuel that never runs out) such as wind energy, can generate electricity profitably, without the harmful emissions that conventional power stations produce. On the other hand, wind projects may have associated drawbacks. For example, some feel they spoil the landscape.

Wind Power

4) Are you in favour or against the production of electricity from wind power?

5) What, if anything do you feel is the primary advantage of wind power:
- renewable energy,
- safe,
- non polluting,
- local power source,
- other.

6) What, if anything is your primary concern over wind energy:
- visual intrusion,
- noise,
- safety,
- danger to wildlife,
- loss in property price,
- other.

7) Are you aware of the windfarm at Hagshaw Hill?

8) How do you feel about Hagshaw Hill wind farm:
- visually? (Like it, neutral, don't like it)
- noise? (No problem, neutral, a problem)
- other?

9) Would you like to:
- keep the wind farm,
- remove the wind farm,
- neutral.

10) Reasons for response in 9)?

11) Are you in favour of more wind farms?

12) Reasons for response in 11)?

13) Are you in favour of more wind farms locally?

14) Reasons for response in 13)?

15) Which impacts of a locally proposed wind farm would be of high concern to you because of where you live?

- visual,
- noise,
- safety,
- other.

A.2 Contingent Valuation

The questions used in this survey relate to the Hagshaw Hill and Pagie Hill surveys. Open ended questions are used in many instances to elicit the respondents true opinion rather than a forced answer. This is particularly important in regard to determining the motivation for the contingent valuation returned.

Introduction

Good morning/afternoon/evening, I'm calling with you on behalf of Edinburgh University. We are interested in what people who live near to windfarms think of them and any costs they may incur. (Select person over 18 at next birthday). Would you mind taking around 15 minutes to answer some questions? All answers will be anonymous and strictly confidential.

Sample Characteristics

1) Is this your main residence?

2) Do you own this property?

3) How long have you lived at this property?

Background and Scene Setting

We all expect a reliable and economic supply of electricity to meet our everyday energy needs. The production of electricity is normally from nuclear or fossil fuels (such as coal, oil and gas) which produce pollution or hazardous wastes. The pollution from fossil fuels contributes to climate change and global warming. It is recognised as one of the greatest threats facing our environment.

Scotland is blessed with an abundance of wind. Renewable energy projects (those using a fuel that never runs out) such as wind energy, can generate electricity profitably, without the harmful emissions that conventional power stations produce. On the other hand, wind projects may have associated drawbacks. For example, some feel they spoil the landscape.

Wind Power

4) Are you in favour or against the production of electricity from wind power?

5) What, if anything do you feel is the primary advantage of wind power:
- renewable energy,
- safe,
- non polluting,
- local power source,
- other.

6) What, if anything is your primary concern over wind energy:
• visual intrusion,
• noise,
• safety,
• danger to wildlife,
• loss in property price,
• other.

7) Are you aware of the windfarm at Hagshaw Hill?

8) How do you feel about Hagshaw Hill wind farm:
• visually? (Like it, neutral, don't like it)
• noise? (No problem, neutral, a problem)
• other?

9) Would you like to:
• keep the wind farm,
• remove the wind farm,
• neutral.

10) Reasons for response in 9)?

11) Are you in favour of more wind farms?

12) Reasons for response in 11)?

13) Are you in favour of more wind farms locally?

14) Reasons for response in 13)?

15) What is your approximate monthly spend (£) on electricity?
1-14, 15-29, 30-44, 45-59, 60-74, 75-99, >100

Valuation - only for those respondents who can see the windfarm from their home

16) Producing electricity locally provides a more reliable and efficient supply than if the electricity had to travel over long distances. Local wind produced electricity can therefore cost less than electricity imported from elsewhere. With this in mind would you wish to pay more for your electricity and have the wind turbines and their visual impact removed. If you would be willing to pay to remove this visual impact, by how much (£) on your monthly bill? (We look for a monetary response as this is the way we can best judge the reality of public opinion - putting your money were your mouth is so to speak.)

17) Reasons for this valuation?

Supplementary questions are either added to the questionnaire above or inserted in place of questions 16) and 17) as required. The supplementary questions regarding the proposal for a new windfarm are listed below.

Example Proposal - Pagie Hill

Pagie Hill has been selected as a possible site for a wind farm. The map shows the area surrounding Pagie Hill. (Show respondent map.)

The proposal for the Pagie Hill wind farm is likely to consist of up to 5 wind turbines, each with a capacity of 600 kilowatts (kW). This gives the wind farm an installed capacity of 3MW. The electricity generated would be fed into the local electricity grid system, and a stone access road built for the construction and maintenance of the turbines. Each year the wind farm would generate enough electricity to meet the annual needs of around 2,000 Scottish homes. The turbines will have 3 blades and a tubular steel tower of approximately 45 metres in height. Each blade will be 22m long.

It is understood that besides any benefits such a wind farm might produce there may also be negative impacts on the local area.

18) What is your initial reaction to this proposal? (Oppose, neutral, support.)

19) Reasoning for response in 18)?

20) Which impacts of this proposed wind farm would be of high concern to you?

21) The developer has identified the site at Pagie Hill as profitable from a technical point of view, however it is realised that there may be impacts which cost those nearby. Which impacts of this proposed wind farm would be of high concern to you because of where you live?

- visual,
- noise,
- safety,
- other.

22) As previously mentioned locally produced wind energy may be cheaper than that imported from elsewhere. How much more would you be prepared to pay (£) on your monthly electricity bill to prevent the project being constructed and thereby not cause you any visual impact?

23) Reasons for this valuation?

The questions 24) and 25) are only for those respondents selected to return a qualitative assessment of the new true-cost optimised windfarm layout over that of the traditional cost optimised windfarm.

24) Viewing the photographs of the two alternative windfarm layouts, which do you think is better (visually)?

25) What is the reason for your response in 24) ?

The final information to be presented to the respondent.

The results of this survey are completely anonymous and will be used in minimising the impact of future windfarms. Please note that the Pagie Hill windfarm is only a theoretical example to get responses for the study. As far as we are aware **NO** development has been, or will be, planned for this site.

Thank you for your time in completing this survey.

A.3 Example Photomontage Visualisation

Figure A.1 illustrates an example of the photomontages derived for the sample population providing CV responses. The windfarm displayed is the initial manually input layout for Pagie Hill viewed from the village of Glespin (UK grid reference 280923, 628540).

Figure A.1: Visualisation of initial Pagie Hill windfarm from Glespin.

A.4 Example VR Visualisation

Figure A.2 illustrates an example of the VR scene derived to assist the developer in predicting visual impact. The windfarm displayed is the final true-cost optimised layout for Pagie Hill. This output is directly derived from ExWind, the ground coverage being determined by the current ExWind map display, in this case the OS 1:50,000 Landranger of the area in question. The VR scene is fully interactive.

Figure A.2: Virtual Reality visualisation of Pagie Hill windfarm towards Glespin.

Appendix B

National Visibility Analysis

In order to undertake a visibility analysis at a national level, significant computing resources are required. For example, Scotland has an area of $\approx 78,133\text{km}^2$ Assuming that:

- Half the area is not suitable for development of any type (water, populated, already developed or designated area).
- Fast running code is generated using Fortran or similar.
- The cell resolution is 2500m^2, range of visible area is 15km and the artefact heights are 40m, 50m, 60m, 70m, 80m.
- An efficient algorithm developed in-house is used (requires 67,600,000 floating point operations per visibility calculation).

The total number of floating point operations required is then 5.5×10^{15}. The approximate time and costings for carrying out such a study are summarised in Table B.1. The results are based on the systems available at Edinburgh Parallel Computing Centre working at nominal peak performance on a single job. Time to complete the jobs are independent of reading information from RAM of the associated dataset ($\approx$ 16MB).

Machine	GFlops	Time to complete (hours)
Pentium PC	0.5	2872 hrs
Sun HPC3500	6.4	239 hrs
Cray T3E - 900/LC	309.0	5 hrs

Table B.1: National Visibility Computation

Appendix C

Published Papers

Connor, G. and Whittington, H.W.: *True Costing Evaluation Including Externalities of Wind Energy Utilising a Geographical Information System*, Universities Power Engineering Conference, Napier University, Edinburgh, 8-10 September 1998, pp395-398.

Connor, G. and Whittington, H.W.: *A Vision of True Costing*, Publication Pending, Engineering Science and Education Journal, IEE, 2000.

TRUE COSTING EVALUATION INCLUDING EXTERNALITIES OF WIND ENERGY UTILISING A GEOGRAPHICAL INFORMATION SYSTEM.

G. Connor, H.W. Whittington
The University of Edinburgh, UK

ABSTRACT

Indicators from recent studies and legislation support that in the near future, further provision for energy originating from renewable resources will be made. This paper outlines the reasons behind this move to renewable energy sources, and the likely future for such technology. The inconsistencies that exist in the energy market today are highlighted, defining the need for a tool to better evaluate potential for a sample technology; viz. wind energy projects from all relevant factors. The development of such evaluation software utilising a Geographic Information System (GIS) is then described.

1. THE FUTURE PROVISION OF ENERGY

There has been an increased interest expressed in renewable energy sources to meet growing demand for a number of reasons. Renewable energy technology:

1. Uses locally available sources of decentralised energy supply.
2. Does not contribute significantly to acid rain.
3. Produces energy largely free from greenhouse gases.
4. Diminishes reliance on imported energy sources thus increasing security of supply of input energy.
5. Substitutes valuable fossil fuels.

Based on the above criteria the European Community (EC) has recently committed to achieving a goal of 12% of gross energy consumption penetration by renewables by 2010. Currently renewable energy supply accounts for less than 6% of gross inland energy consumption [1]. The present and predicted contributions of renewable energy to EC energy consumption are depicted in Figure 1.

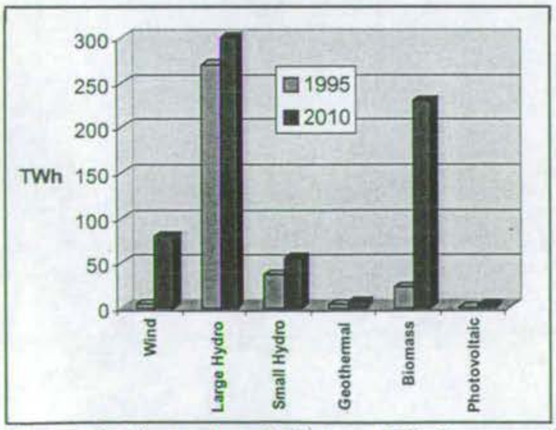

Figure 1: **Current and Future EC Sources of Renewable Energy [2]**

As a reflection of EC policy the British government continues to implement a number of legislative measures. The Scottish Renewables Obligation round 2 (SRO-2) and the Non Fossil Fuel Obligation round 4 (NFFO-4) are to follow on from and build upon the previous versions of the same orders, beginning 1st May 1997. NFFO-4 requires arrangements to be made in England and Wales for 843 MW of new renewable generating capacity before 30th December 2016 [3].

The envisaged choices available to produce this requirement from renewables in the UK may be taken to be those described as:

1. Hydro – remaining resource less than 2.3TWh per annum [4].
2. Biomass – recoverable potential of 16.3 million tonnes of oil equivalent per annum (Mtoe/a) from energy crops and 24.6 Mtoe/a from wastes [5].
3. Solar – 'passive solar design' for building heating show most promise at present.
4. Wind – extremely promising due to most favourable wind conditions in Europe, both onshore and offshore.

2. ENVIRONMENTAL CONFLICT

It is often observed that, unfortunately those natural characteristics that allow renewable energy potential (e.g. large tidal variation, high and windy area, etc.) are often those areas of natural importance either from an ecological or amenity point of view.

The energy systems planning engineers' task is therefore complex, attempting to produce the true optimum trade-off (technological and environmental) for the maximum 'social' benefit to all parties. This introduces the idea of welfare economics were the main thrust is to maximise welfare through optimal resource allocation. At present there are very few reliable tools or methodologies to produce such an encompassing solution. If a direct comparison could be made between, for example, the decrease in the population of wild life in a given region by the promotion of a tidal scheme as against the development of a coal-fired power station, then a method for direct comparison in this matter between these two fuel cycles would be apparent.

Because of the large range of factors from human and social effects through to ecological affects such as those previously mentioned it is unlikely that a direct comparison will be possible. Thus, to achieve some level of evaluation of different effects, some common bases of comparison must be developed.

It is traditional to evaluate projects in monetary terms. However there exists a danger that economic theory is seen as fully definitive.

3. EXTERNALITIES

Externalities are defined as:
The costs and benefits which arise when the social or economic activities of one group of people have an impact on another, and when the first group fail to fully account for their impacts [6].

e.g. the unaccounted for costs incurred due to SO_2 pollution from fossil fired power stations increasing associated lung and respiratory disorders and hence the burden on the National Health Service.

There is wide acceptance that the generation of electricity causes damage to a wide range of receptors. These damages are referred to as external costs, or externalities, because they are not reflected in the market price of energy.

If it were possible to evaluate the value to society of energy generation it would also be possible for the energy systems engineer to opt for the 'best' trade-off in any given situation thus appeasing the electrical appetite of consumers along with the highly relevant concerns of the environmental lobby. Presently the evaluation techniques used to choose fuel cycle and energy technologies do not normally incorporate externalities in cost-benefit studies.

3.1 Driving Factors

The driving factors behind the valuation of externalities are:

- the application of economic instruments to environmental policy,
- the integration of environmental concerns,
- the encouragement of market mechanisms,
- the evaluation of stricter environmental standards,
- the indication of a technology's environmental performance,
- the development of environmentally adjusted accounting.

3.2 Methods for External Cost Valuation

There are a number of methods commonly used to place a monetary value on a defined externality.

3.2.1 Contingent Valuation:
A sample of people questioned as to their monetary bids concerning 'willingness to pay' (WTP) to have or not to have a good, and 'willingness to accept' (WTA) to accept having or not having a good.

3.2.2 Hedonic Pricing:
The increase or decrease in the monetary value of property associated with a change to the local environment of one type or another.

3.3.3 Travel Cost:
The monetary value people are willing to pay to travel for a certain amenity or good, reflecting demand for that amenity or good.

3.3.4 Dose-Response Functions:
The direct linking of a 'dose' of some kind (e.g. pollution) to its 'response' and therefore monetary cost (e.g. increased medical costs) via definite pathways expressed mathematically.

3.3 ExternE

An EC study 'ExternE' has set out a methodology for the evaluation of all common energy producing fuel cycles. Figure 2 illustrates the 'Impact Pathway' methodology utilised [7].

Figure 2: **ExternE Impact Pathway Methodology**

Although valuable when estimating external costs, ExternE is fairly general and there will be problems when attempting to evaluate a specific site accurately.

3.4 Difficulties and fallacies with Externalities

These difficulties include:

1. Transferability of valuation to another situation.
2. Uncertainty of pathways.
3. Discounting the future.

4. False economic valuation due to free-riding, socio-economic status of those interviewed, and other unallocated economic factors.

It must however be noted that though a perfect solution to valuing externalities is not presently available, the existing methods should be used to attempt to rectify what are unaddressed issues, namely the accurate assessment of the cost of the exploitation of energy resources from all relevant factors.

4. WIND ENERGY IN THE UK.

At present there are 725 wind turbines (of over 200 kW, 309MW installed capacity) producing approximately 817 GWh per annum in the UK [8]. To meet the government target of 10% of all electricity supply being renewable by 2010 the UK requires further renewable resource development. Britain has a good wind resource (Scottish averages classed as >6m/s in sheltered terrain, and >11.5m/s on hills and ridges) [9]. Since plans envisage that much greater use of this resource is possible it is relevant to study this energy source . The following are the difficulties with such development.

Environmental Impacts:
- loss of landscape and visual amenity (coincidence with National Parks etc.),
- ecological,
- electro-magnetic interference (EMI),
- acoustic noise.

Technical Considerations:
- wind resource,
- remoteness of site for grid connection, highway access, and maintenance,
- ground condition
- ground topology.

These constitute the basic parameters of the technical and economic challenges. In order to take all the above into account a methodology must be derived to evaluate fairly all the above 'costs' or 'benefits' in monetary terms and thus derive under which conditions windpower is more attractive than other options.

Such a study would deal with large amounts of data on various factors, most of which depend extensively on geographic location. It is therefore intuitive to use geographic location as a framework for such a study. The tool designed to store and display such geographically referenced data is known as a Geographical Information System (GIS). Two possible applications of GIS will be described.

5. GIS

Geographical Information Systems may be defined : '*as a computer based tool integrating database operations such as query and analysis with the visualisation and geographic benefits offered by maps*' [10].

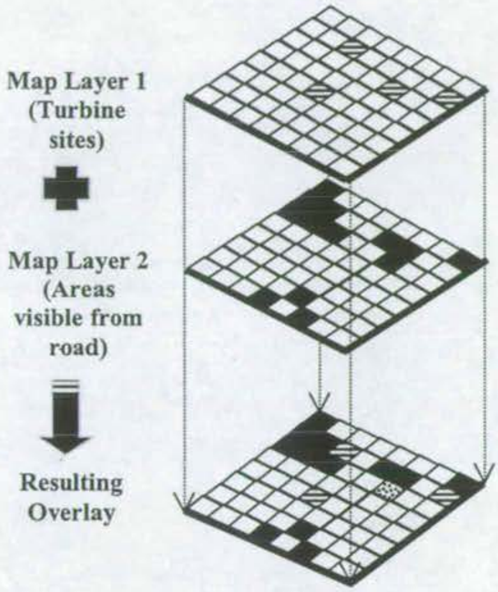

Figure 3: **The Use of GIS Raster (Grid) Overlays**

6. DESIGN AID FOR THE EVALUATION OF A WIND ENERGY SITE

The aim is to produce software capable of evaluating all relevant costs, technical and environmental, specific to a renewable resource, in this case, wind energy.

Input consists of all relevant locational and technical details for the proposed wind project, each locational attribute being stored as a distinct GIS map layer. Digital mapping and associated data are available from the Ordinance Survey (OS) through the 'Digimap' trial. Further geographical data is sourced from field survey, while technical data is entered and stored in a database.

Processing is carried out on each distinct physical or environmental site characteristic as a series of map layer manipulations. Figure 3 demonstrates processing by an overlay of two map layers. The resulting map pinpoints where a proposed turbine site is visible from a nearby road. A similar method may be used to derive the members of the local population for whom the wind farm will be visible.

6.1 Visual Impact Assessment

Visual impact is regarded as a prime example of an external cost for wind power. Visual amenity is highly subjective and therefore is extremely difficult to quantify. Each individual viewing a wind farm brings a personal attitude and perception of the visual impact, and hence a personal acceptability in monetary terms. It is crucial at the design stage to produce a visualisation of the proposed wind farm if accurate external costs are to be calculated. This allows participants in a contingent valuation questionnaire to decide accurately their WTP and WTA for the project being evaluated.

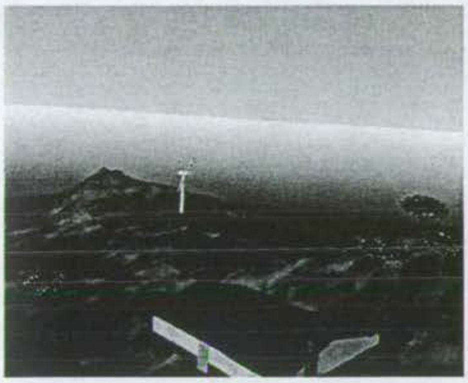

Figure 4: **VR Output from Software**

The GIS software under development addresses this issue by creating a virtual reality (VR) world in which a visitor may explore the proposed wind farm development. Figure 4 illustrates such a VR scene.

A total external cost for visual amenity is calculated from a number of participants' personal valuations. The external cost for visual amenity is therefore derived and may be added to the total project cost. The planner may thus also directly trade-off the external costs against mitigation costs for maximum benefits to all concerned.

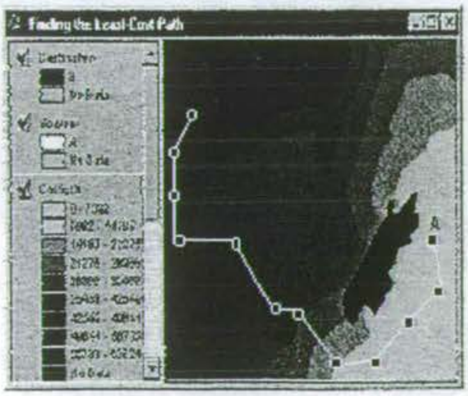

Figure 5: **Least-Cost Path Routing**

6.2 Least-Cost Path Infrastructure Routing

Once all costs (external and traditional) are derived on the basis of geographic location (i.e. a cost map), the GIS produces a least-cost path. The least-cost path defines the cumulative least-cost from a source (e.g. wind farm) to a destination (e.g. existing grid connection). Figure 5 demonstrates a least cost path for distribution lines from turbine 'site A' to destination 'site B' the local existing distribution network. The least-cost route for a connecting road is evaluated in a similar manner, for maximum benefits.

7. CONCLUDING COMMENTS

There may exist a distortion in favour of technologies with significant environmental impact. This paper discusses methods for a more extensive assessment of fuel cycles by including external costs. Software is under development utilising a GIS specifically to evaluate wind energy projects as the expansion of wind power is expected in the foreseeable future. This software quantifies external costs in order to introduce true market mechanisms and aid in the further development of renewable energy resources.

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A VISION OF TRUE COSTING.

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ABSTRACT

In recent years, most new generating plant installed in the UK electricity supply industry has been gas turbine. In the near future, this trend could change as both environmental pressures and international agreements legislate towards a significant increase in the level of exploitation of renewable energy. Options for new generating plant must be assessed and compared using several bases before a choice is made. This paper describes the initial stages of development of techniques to accommodate externalities into the decision-making process. An illustrative example, wind energy, is presented.

1. EXTERNALITIES AND ELECTRICITY OPTIONS

The primary energy options available for new generation in electricity supply networks, include the fossil fuels, nuclear and renewable energy (RE).

Traditionally decision-making on which option to use in system expansion was based largely on a least-cost criterion, where the full economic costs of each option were determined and that with lowest cost adopted. However, even with this approach, the exercise was often distorted by issues lying outside those of economics. For example, for many years successive British Governments applied pressure to the Nationalised Electricity Supply Industry (ESI) to build power stations which used coal mined in the UK.

Freed from Government direct intervention, the privatised ESI has applied rigorous economic criteria to power station building, leading to the much-publicised "dash for gas". However, the utilisation of all types of energy has an effect on the environment. (For further information, refer to [1]). National and international environmental pressures are causing changes in project planning and issues outside the normal range now must be taken into account: they are often in the form of "externalities", defined as:

> *the costs and benefits which arise when the social or economic activities of one group of people have an impact on another, and when the first group fail to fully account for their impacts [2].*

1.1 ExternE

ExternE, an EC study, comprises a comprehensive attempt to refer a wide range of human activity to the common denominator of monetary cost or benefit. ExternE includes analysis of all common energy producing fuel cycles and its basic concept has been adopted in our analysis. The general ExternE methodology uses an 'Impact Pathway' methodology, Figure 1 [3].

The use of financial tools in environmental issues is reasonably well accepted already. For example, it has been argued that a levy (Climate Change Levy) should be applied to gaseous and other emissions from fossil-fired power stations: this basic concept should act as a disincentive to polluters.

The concepts promoted in ExternE suggest taking this process further. Fossil fuel burning causes emissions which may cause an increase in lung and respiratory disorders and hence place a financial burden on the National Health Service. It may be argued that the cost of such an externality should not be met by the NHS but by some other body, possibly the fossil-burning plant operator.

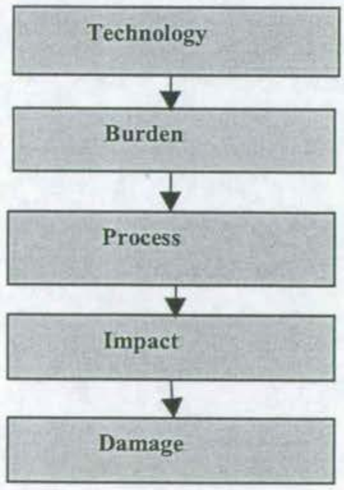

Figure 1: **ExternE Impact Pathway Methodology**

The Electricity Act 1989 requires generators to take full regard of environmental issues (externalities), viz.,

> *the Generator or Supplier of electricity shall have regard to the desirability of preserving natural beauty, of conserving flora, fauna and geological or physiographical features of special interest... [4].*

If it were possible to determine comprehensively the costs and benefits to society of different methods of electricity generation, it would also be possible to opt for the 'best' trade-off in any given situation. The task would be to satisfy simultaneously the electrical appetite of consumers and the relevant concerns of the environmental lobby. Presently this is not done as the evaluation techniques used to choose fuel cycle and energy technologies do not normally incorporate the full range of externalities in cost-benefit studies. In this paper, we describe the early stages of the development of a suitable tool-set to include externalities in primary energy choice.

1.2 The Drivers

The major drivers behind the valuation of externalities include:

- the application of economic instruments to environmental policy,
- the integration of environmental concerns,
- the encouragement of market mechanisms,
- the evaluation of stricter environmental standards,
- the indication of a technology's environmental performance,
- the development of environmentally adjusted accounting.

1.3 Methods for External Cost Valuation

We will now explain how a monetary value can be ascribed to an externality.

1.3.1 Contingent Valuation (CV):

Here a sample of those likely to be affected by an undertaking are asked to estimate in financial terms, their 'willingness to pay' (WTP) to have, or not to have, the undertaking, and their 'willingness to accept' (WTA) to accept having, or not having, the undertaking.

1.3.2 Hedonic Pricing:

This accounts for the increase or decrease in the value of property because of a change to the local environment. An example would be the reduction in the selling price of someone's house because a cement factory had been built near the house.

1.3.3 Travel Cost:

The monetary value people are willing to pay to travel for a certain amenity or good, reflecting demand for that amenity or good. For example, people are willing to pay to travel to areas where they can enjoy hill walking. Part of the enjoyment and hence WTP for this activity, are the views offered to those walking.

1.3.4 Dose-Response Functions:

The direct linking of a 'dose' of some kind (e.g. pollution) to its 'response' and therefore monetary cost via definite pathways expressed mathematically. For example, a formula could be developed which relates increasing levels of aircraft noise near an airport to the extra cost of mitigating such noise by introducing double-glazing.

1.4 Difficulties with Externalities

While suggesting that a more realistic and broad evaluation of project options might be offered by including externalities, we appreciate that several difficulties exist with this approach. These difficulties include:

1.4.1 Transferability of valuation:

Local features merit separate valuation if accuracy is to be consistent. For example, the cash incentive to work in conditions of danger or with a risk of injury is likely to be much higher in a developed country than a developing country.

1.4.2 Uncertainty of pathways:

Pathways may be extremely complex and largely unknown, therefore non-quantifiable. For example, it is very difficult to quantify costs specifically associated with the care of additional skin-cancer patients, who may have contracted the condition as a result of the reduction in ozone levels in the stratosphere.

1.4.3 Discounting the future:

Greater value is placed on a "good today" because of uncertainty and risk associated with factors governing the value of a "good tomorrow". For example, if it were possible to pay not to have a power station nearby, many would be prepared to spend more (as an average per annum) in the short term rather than make a long-term financial commitment because of uncertainties about the future.

1.4.4 False economic valuation:

There is evidence that distortions are caused by factors such as free-riding by some members of society, by the differences in perception by different socio-economic groups interviewed and other unallocated economic factors.

Despite the present lack of precision, an externality measurement technique, if developed, could offer a valuable and extremely useful tool to systems planners. Because renewable energy (RE) has received much attention recently and because it is often considered environmentally benign, we have chosen one of the RE front-runners, an inland wind energy installation, to illustrate our work.

1. RENEWABLE ENERGY IN THE EU

The European Union (EU) has recently committed to achieving a goal of 12% of primary energy consumption by renewables by 2010.

Currently renewable energy penetration is confined largely to the electricity supply networks and accounts for less than 6% of gross inland energy consumption [5]. The present and predicted contributions of renewable energy to EU energy consumption are depicted in Figure 2.

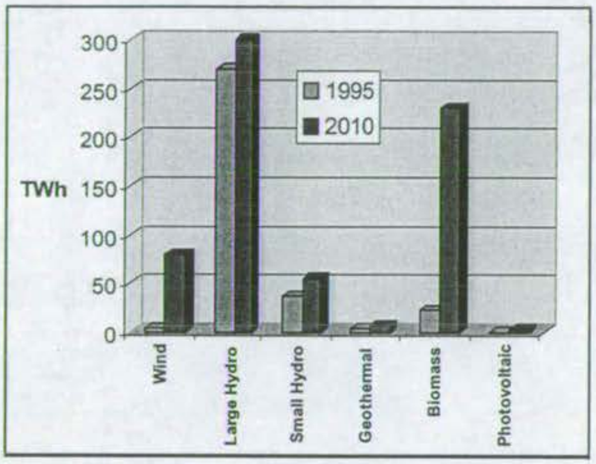

Figure 2: **Current and Future EC Sources of Renewable Energy [6]**

In response to EU policy, and for other reasons, the British government continues to implement a number of legislative measures. The recent Scottish Renewables Obligation round 3 (SRO-3) and the Non Fossil Fuel Obligation round 5 (NFFO-5) followed on from, and build upon, the previous versions of the same orders. For example, SRO-1 (initiated 1994) as illustrated in Table1 listing the various technologies awarded contracts.

	Total		*Commissioned*	
Technology	No. of Projects	MW	No. of Projects	MW
Wind	12	45.6	6	21.8
Biomass	1	9.8	0	0
Hydro	15	17.3	3	2.3

Table 1: **Current Status of SRO-1 Projects [7]**

Table 1 shows that a large number of projects remain incomplete. While project lead-time is one factor responsible, it is often at the planning stage that projects are delayed or even rejected. Usually this is because of local opposition due to external costs.

3. ENVIRONMENTAL CONFLICT

In environmental terms, it is unfortunate that RE potential is often located in areas of great natural sensitivity, either in terms of ecology or of amenity. Those responsible for system planning face a complex task in attempting to produce the best trade-off (technological and environmental) for the maximum social benefit to all parties.

This is often termed "welfare economics" which has, as its main thrust, the maximisation of society's welfare through optimal resource allocation. In electricity supply, this entails an evaluation of primary energy options which addresses all (or as many as are relevant) of the issues that are contained under the umbrella of welfare economics. Although the ESI is sensitive to such issues, unfortunately, at present, there exist very few reliable tools or methodologies to produce such an encompassing solution.

For example, it is virtually impossible to make a direct comparison between

a) the ecological consequences of the decrease in the population of wild life resulting from the promotion of a tidal energy scheme and
b) the environmental impact of the development of a coal-fired power station.

This is largely because of the wide range of factors involved, from human and social effects through to those of ecology.

Despite these difficulties, there is evidence that electricity supply projects are now being promoted preferentially in circumstances where the favoured option is not that of traditional least financial cost. This occurs most obviously in the UK with the NFFO and SRO (see section 2), where part of electricity demand is essentially "ring fenced" for reasons other than cost.

To cope with the problems of comparability a common base for comparison is adopted and all elements referred to that base, (for example ExternE uses monetary cost).

4. WIND ENERGY IN THE UK

Wind energy has been chosen as an illustrative example because it represents a significant energy resource and because it has been well supported in both NFFO and SRO. It is also a good example since it appears to be at a transitional stage in terms of public acceptance. For example, it appears that the relatively low level of promotion of wind energy schemes in England and Wales is because planning applications for wind farms are less likely to be granted today than a few years ago. The Planning Authorities in Scotland appear still willing to look positively on applications.

At present there are 725 wind turbines (of over 200 kW, 309MW installed capacity) producing approximately 817 GWh per annum in the UK [8]. Britain has a good wind resource (Scottish averages classed as greater than $6ms^{-1}$ in sheltered terrain, and greater than $11.5ms^{-1}$ on hills and ridges) [9].

4.1 Technical considerations of Wind Energy

Although this paper is not concerned with detailed technical design procedures for wind energy schemes, our methodology and software under development takes account of technical factors such as.

4.1.1 ***Wind resource:*** Wind energy, hence electrical output, varies as the cube of the available wind speed.

4.1.2 ***Remoteness of site for grid connection, highway access, and maintenance:*** The length of the electrical connection determines voltage drop and power loss. Such infrastructure construction costs increase with distance.

4.1.3. ***Ground condition and topology:*** The specific site affects both construction and infrastructure routing costs.

4.2 Environmental considerations of Wind Energy

Of the wide range of features included in any study of power station externalities, environmental impact is pivotal. Wind energy environmental impacts include the following:

4.2.1 ***Loss of landscape and visual amenity (coincidence with National Parks etc.):*** In the UK, the areas with useful windspeeds are predominantly upland or coastal areas that tend to coincide with nationally designated areas of beauty and amenity.

4.2.2 ***Ecological impact:*** Wind energy development tends to be in unspoilt areas and the impact on what is often important local ecology must be carefully investigated.

4.2.3 ***Electro-magnetic interference:*** The large structure of a wind turbine causes reflection, scattering, and diffraction of radio signals. The periodic movement results in a periodic disturbance by Doppler shifting.

4.2.4 ***Acoustic noise:*** Mechanical noise, emitted by the moving parts, and aerodynamic noise affects the surrounding area.

4.2.5 ***Life-cycle greenhouse gas emissions:*** Although low (two orders of magnitude less than coal generating plant of the same rating), there remains some emission of greenhouse gases associated with the equipment lifecycle, [10].

These constitute the basic parameters of the technical and environmental challenges to be fairly evaluated by the developer of a wind energy scheme.

5. WIND ENERGY, THE ENVIRONMENT, AND PUBLIC PERCEPTION

While the resource is termed as renewable, it is not always regarded as benign. Several countryside groups are exerting pressure for change in the way wind energy is exploited. Recent statements such as the following summarise their concerns:

> *'wind turbines now intrude into some of the most unspoilt landscapes in Britain and the damage is set to continue unless there are real changes to the way in which the industry is financed and regulated' [11].*

This reaction to wind energy often stems from perception rather than quantitative analysis, but it represents a significant impediment (cost) to future wind projects.

In contrast, support for wind power and other renewables is often on an abstract environmental level rather than on the specific level of local implementation. To illustrate this, we refer to the results of a survey carried out in Wales. It was found that 70% of the Welsh would support wind power generally, whereas, when surveyed concerning three specific local sites, only 40% of those surveyed were positive [12].

Interestingly, opponents will often value more highly local aesthetics than any risk of climate change or nuclear power, real or perceived.

To highlight the subjective nature of local amenity (visual and noise) we have summarised the findings of Damborg and Krohn [13].

- A similar audible noise level from turbines is perceived to be of greater nuisance by men than by women.
- Women prefer groups of 2 - 8 turbines rather than large wind parks.
- Men prefer wind parks of 10 - 50 turbines.
- Those who are middle-aged are likely to be more critical.
- Spinning turbines are more acceptable than idle ones.
- City dwellers are more negative about windfarms than their rural counterparts.
- A higher proportion of people are in favour of windpower after such a project is completed in their locality than during its planning and construction.

We have attempted to quantify all the above and many other previously unallocated factors by deriving a monetary valuation based on affected individuals perception.

The route we plan to use to test the acceptance of a beneficial project by the majority of the local populace will include:

- optimisation based on the comparison of traditional costs and benefits, further clarified by the inclusion of external costs.
- local information, consultation and participation in the planning of any proposed development, provided partly by contingent valuation survey methods to quantify public attitudes and opinion in actual monetary terms.
- possible use of acceptable cost-effective mitigation against 'show-stoppers' and large areas of external cost derived on a greatest benefit to all basis.

6. EVALUATION OF POTENTIAL WIND ENERGY SITES

Candidate regions for wind power development are normally identified according to wind resource, topology, landuse, proximity to grid connection and road access. Any environmental impact assessment (EIA) which is carried out is normally to crudely verify site suitability, rather than aid in initial site selection or optimisation.

6.1 Data Storage and Manipulation

We have selected geographic location as our framework as many of the traditional and external design issues depend on this. The tool designed to store and display such geographically referenced data is known as a Geographical Information System (GIS). A GIS may be described as:

> '*a computer based tool integrating database operations such as query and analysis with the visualisation and geographic benefits offered by maps*' [14].

Input data consists of all relevant locational and technical details for the proposed wind project, each locational attribute being stored as a distinct GIS map layer in ArcView GIS software. Digital mapping and associated data are available from the Ordinance Survey (OS) through the 'Digimap' trial. Further geographical data is sourced from field survey while technical data is entered and stored in an external database.

Processing is carried out on each distinct physical or environmental site characteristic as a series of map layer manipulations. Figure 3 demonstrates processing by an overlay: for ease of interpretation, only two map layers are shown but the technique can accommodate many overlaid layers consisting of such raster 'cell' data.

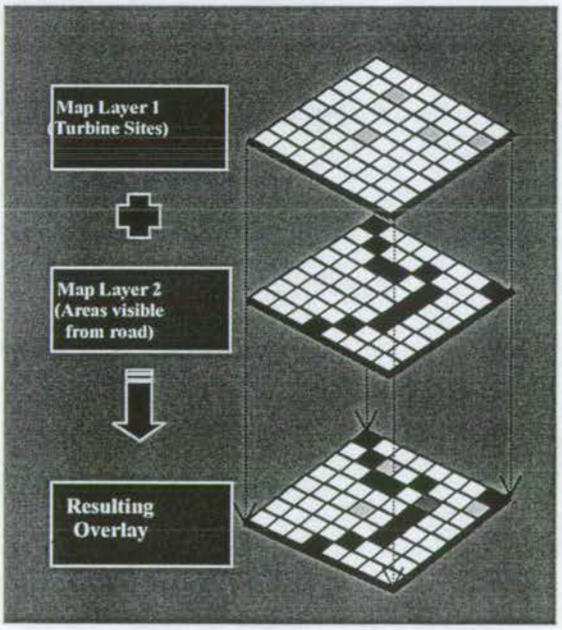

Figure 3: **The Use of GIS Raster (Grid) Overlays**

The resulting example map pinpoints where a proposed turbine site is visible from a nearby road.

6.2 Initial Site Selection

Initially, the development package broadly identifies areas of technically promising wind potential. Parameters evaluated include power availability and density, construction costs and legal constraints. The derived areas are ranked by their potential as possible wind power development sites.

6.3 Quantification of an Externality

We then incorporate external costs. To illustrate the approach that we suggest should be adopted, we next describe how the tool might be used to estimate the level of impact on visual amenity (as the foremost wind energy externality costing) using topological and feature overlay.

6.4 Visual Amenity Valuation

Having identified suitable candidate sites, we apply a visual impact assessment (VIA). The valuation of visual amenity is highly subjective and therefore extremely difficult to quantify. Each individual person viewing a wind farm brings his or her own attitude and perception of the visual impact, and hence a personal acceptability in, say, monetary terms.

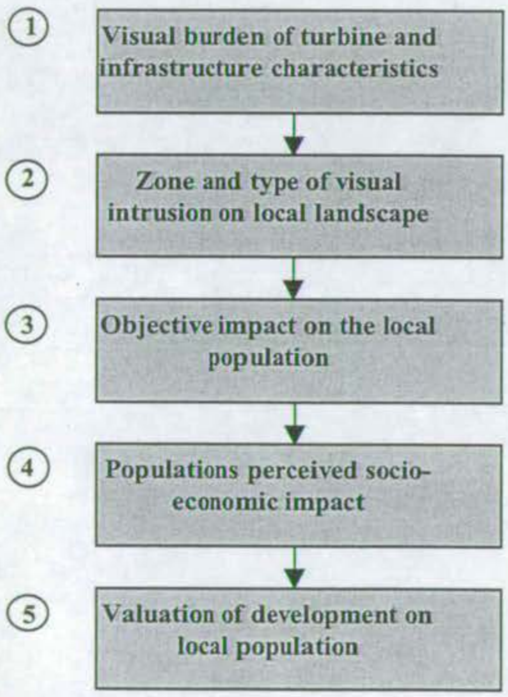

Figure 4: **Visual Amenity Valuation**

Visual impact affects both the inhabitants of the locality and any visitors. Typically, an installation, visible from local roads in the vicinity, (illustrated in Figure 3), may be regarded as visually obtrusive and unacceptable.

The technique addresses visual impact assessment by utilising the visual impact pathway as illustrated in Figure 4. Figure 5 illustrates the implementation of such a pathway using a GIS. Both figures and the text sub-sections are numbered correspondingly.

6.4.1 Topological Data

The GIS software produces a Digital Terrain Model (DTM) from Ordinance Survey (OS) contour data. A DTM is a set of x, y, z co-ordinates, x and y describing map position, and z the elevation at that map point. The turbine positions are entered to enable evaluation of visual quality impacts.

6.4.2 Visual Quality

Visual quality (VQ) indexes at all map points from which the wind development is visible are derived from the DTM via trigonometric and astronomical algorithms. The following are the components of VQ calculated for each point:

- the number of turbines visible,
- the distance from turbines,
- the turbine background (sky or terrain),
- the likelihood of visual flicker and shadow,
- the existing visual amenity.

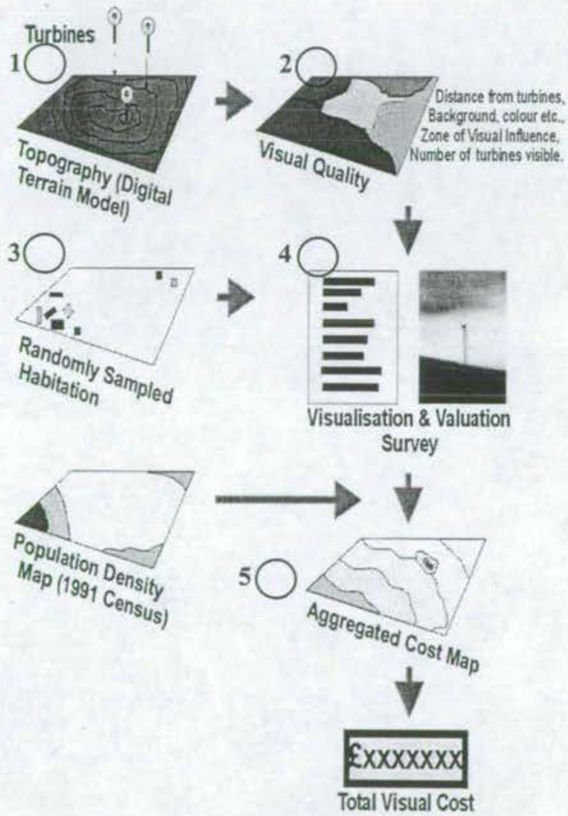

Figure 5: **GIS Visual Amenity Methodology**

For example, an increase in turbine tower height will produce a greater area from which it is visible, hence increasing external cost. Note that the extra tower height means greater cost in materials, but increases the available wind energy and hence electrical power output. By quantifying these benefits and costs, an optimum turbine height may be estimated.

6.4.3 Population Sampling
We next develop a GIS map layer containing all relevant buildings whose occupants might be affected visually (be able to see the installation). The contents of this map layer are then randomly sampled to produce the sample population to be asked to respond to the CV questionnaire.

6.4.4 Project Visualisation
It is crucial at the design stage to produce a visualisation of the proposed wind farm, if accurate visual amenity external costs are to be estimated. Our GIS software addresses the visualisation issue in two ways:

1. by creating a virtual reality (VR) model of the proposed site in which a visitor may explore the proposed wind farm development. Figure 6 illustrates such a VR scene.

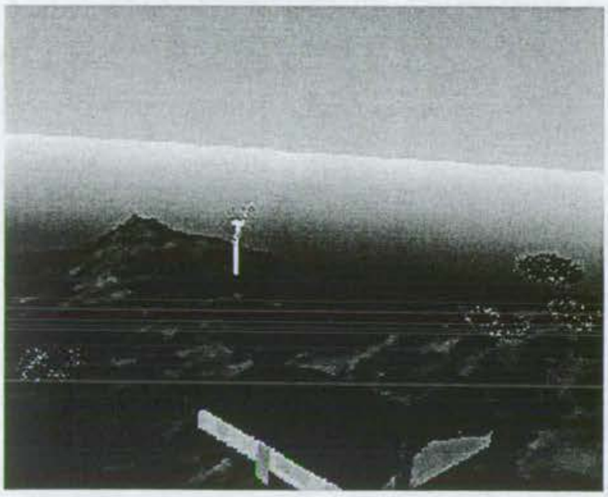

Figure 6: **VR Output from Software**

2. by the application of photomontage techniques from which a more realistic representation may be obtained, hence permitting a more realistic monetary valuation.

The image produced in Figure 6 may be viewed from any angle and allows designers, planners and the general public, if appropriate, to gain an appreciation of the installation and of its potential for visual intrusion. However, we deduced that the quality of such a virtual reality image might be unrepresentative of the final installation.

Because of this limitation, we developed a photomontage technique as illustrated in Figure 7.1 which is a scene typical of many sites considered for wind energy exploitation.

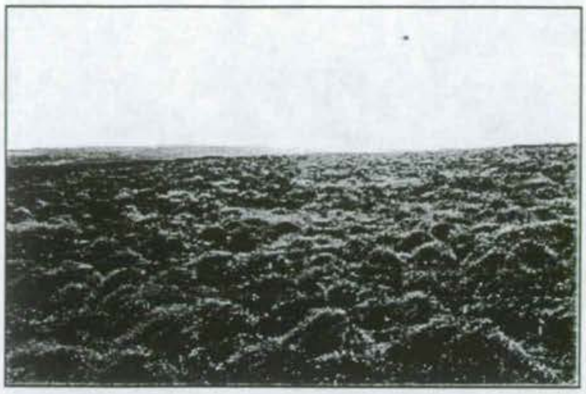

Figure 7.1: **The Original Scene**

The aerogenerators are illustrated in scaled form in Figure 7.2 to create an impression of the scene after installation.

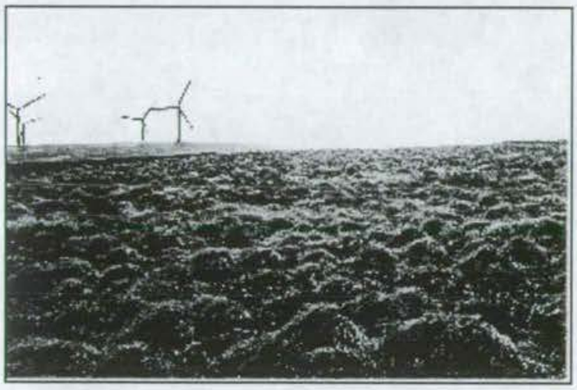

Figure 7.2: **Visualisation of Proposed Development**

In Figure 7.3 we have included another feature of the software, viz., that of demonstrating the visual impact of possible mitigating measures.

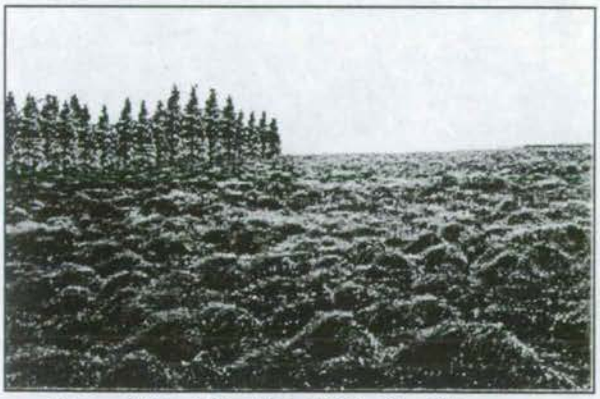

Figure 7.3: **A Possible Mitigation Measure**

Here a line of trees might be used to obscure the wind energy installation; note that the trees should be far enough away from the installation so as not to affect the wind energy at that point. The cost of positioning the trees would then constitute an externality.

Each member of the sample population (section 6.4.3) is visited and a photomontage view from the participants' home is rapidly constructed there using a digital camera and the GIS software.

The personal external cost for visual impact, i.e. loss of visual amenity and mitigation measures, would be calculated from the sample participants' response in the associated CV questionnaire using the photomontage.

6.4.5 Processing of Survey Data

Each personal valuation from the survey is processed and regressed against the visual quality index at that person's home (section 6.4.2). This produces a formula associating monetary values with visual quality. The total external cost from the impact on the visual amenity may therefore be derived by applying this formula (producing visual cost per surveyed person from visual quality) to all map areas and multiplying by the population (1991 Census) in that map area. As a map of the specific visual amenity cost associated with the proposed development has been produced, areas of high external cost may be easily identified.

7. INFRASTRUCTURE ROUTING

Guidelines currently exist that attempt to take note of external factors for distribution networks:

'Wherever possible, new lines are routed to avoid sensitive areas such as nature reserves, archaeological sites and leisure amenity areas.' [15]

Although the wind turbines may constitute the main project cost, infrastructure such as access roads, and grid connection equipment should be evaluated and optimised in a similar manner for both technical and external costs. These would then be added to the total project cost for completeness.

Cost maps of the area surrounding the wind energy development are produced defining the specific costs associated with the construction of the distribution network (both technical and external) in each say, 900m^2 area or raster 'cell'. By overlaying the cost layers and summing vertically adjacent cells (Figure 3) an overall cost map is produced, defining particular infrastructure cost at each map 'cell'.

The GIS then produces a path through the cells defining the cumulative least-cost option from a source (e.g. wind farm) to a destination (e.g. existing grid connection).

Figure 8 demonstrates a least cost path for distribution lines from turbine 'site A' to destination 'site B' the local existing distribution network. The monetary values used are in pounds Sterling (£) per GIS raster 'cell'. In this case, each cell is of 30m by 30m resolution. Costs vary greatly between projects. The average construction cost per metre of 11kV line is £25 [16], increasing depending on locational difficulties. Further costs include operation, maintenance, and site dependent externalities (for example, visual amenity and ecological effects).

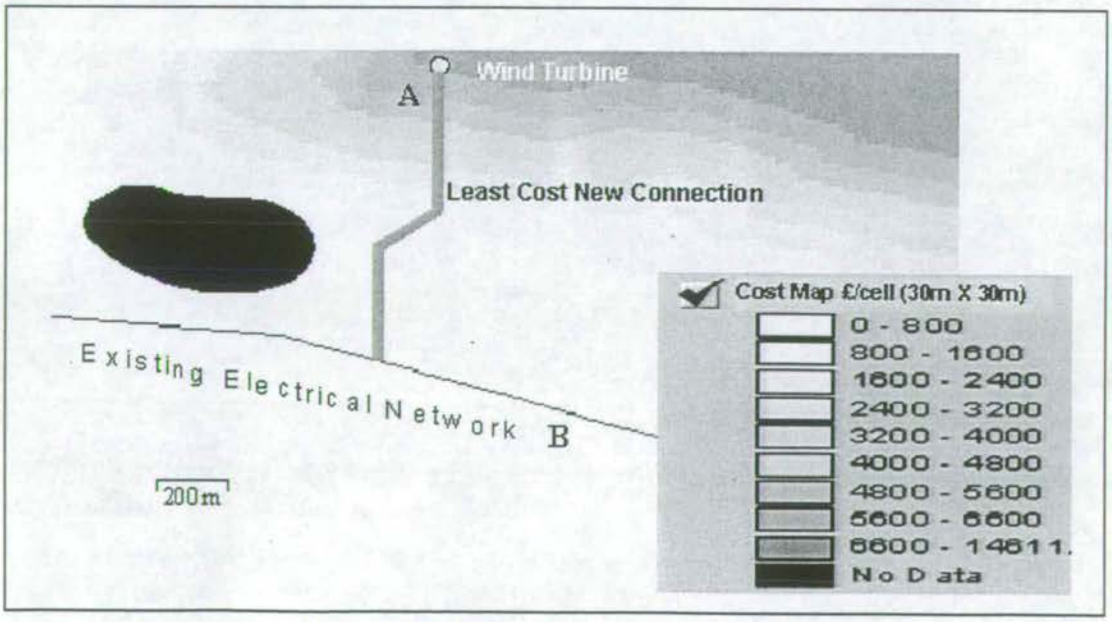

Figure 8: **Example of Least-Cost Path Routing**

Once all costs (infrastructure and windfarm, external and traditional) are derived on the basis of geographic location (i.e. a cost map), candidate sites can be ranked in order of maximising social welfare to all concerned.

8. FUTURE DEVELOPMENTS

- Verification of the derived external cost results by iteratively surveying and optimising a wind power project.
- Incorporation of other fuel cycles into the tool-set.
- Determination by hindcasting of the extent to which previous projects considered external costs, and if the planners got it 'right'.

9. CONCLUDING COMMENTS

We have attempted to show that difficulties may occur if competing options for generation expansion are compared subjectively, especially where there are large environmental-impact components in the comparison. We realise that much care is taken by those involved in the decision-making process at present, but there is still considerable scope for inconsistency in the granting or refusal of planning permission for new generation installations. This paper has described the results of initial work on methodologies which extend the traditional and which attempt to present a regularised approach to environmental-impact assessment.

ExternE has shown very effectively that it is possible to place a monetary value on most human activity and experience. By taking account of all locally derived costs to aid in improved cost-benefit analysis and possible external cost mitigation, improved total project costing will develop further true market mechanisms for expansion planning.

In the UK, already it appears that a major barrier to further development of RE sources is that of external impact, specifically visual amenity. For that reason, we have used visual amenity to illustrate our technique, but it should be emphasised that any full analysis would include the other external costs of acoustic noise, ecological damage, EMI, and potential accidents.

The valuation methods described to help quantify external costs, when used in conjunction with the GIS-based software under development, should permit a more rational and consistent approach to future evaluations of all electricity generating technologies.

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